Baryon Asymmetry from Composite Higgs

Oleksii Matsedonskyi

based on [1803.08546], [1804.07314]
with vonHarling, Bruggisser, Servant

Benasque 2018

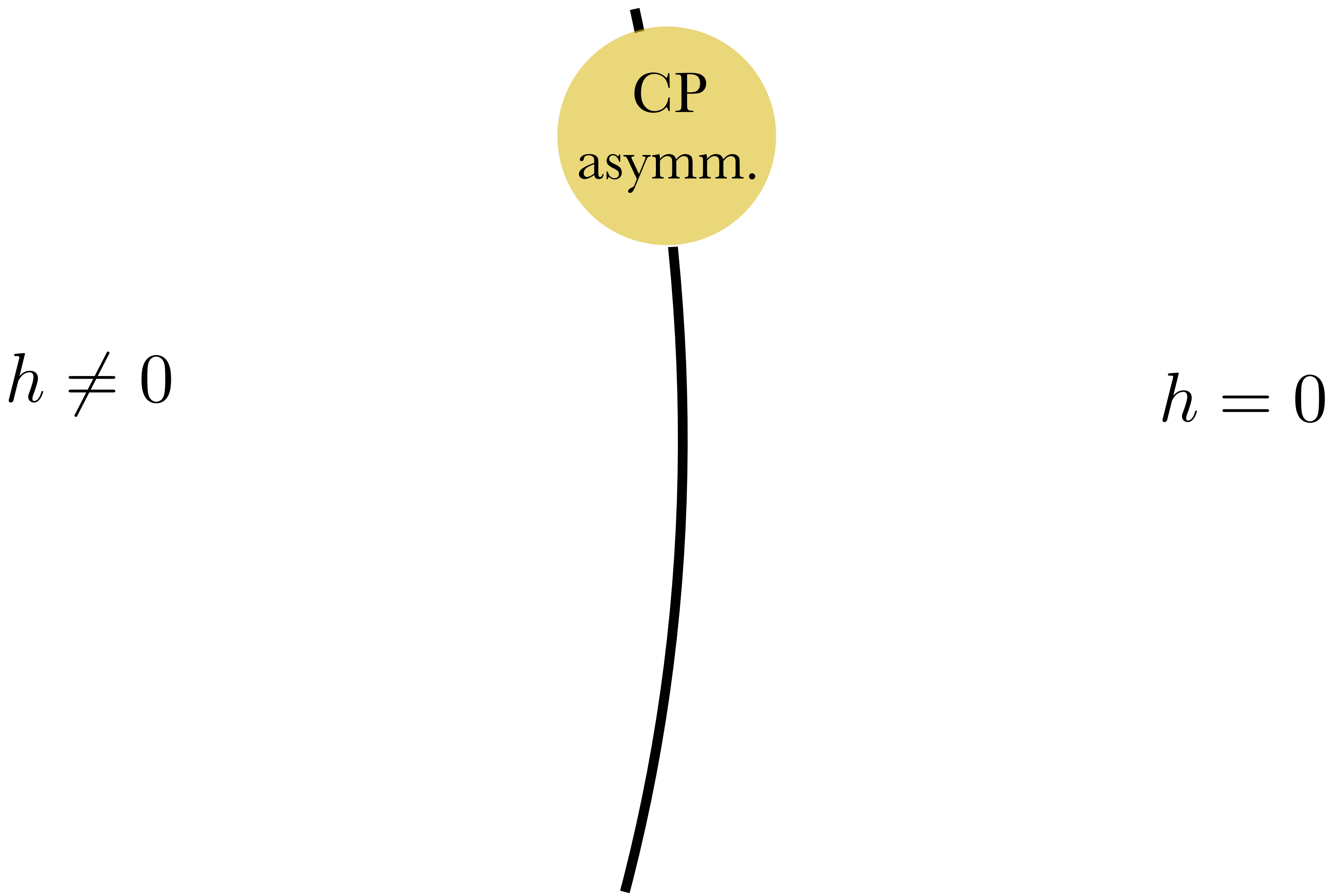
Outline

- EW Baryogenesis
- CH
- EWPT in CH
  - Dilaton potential
  - Transition strength
- CPV
  - Varying top Yukawa
  - Effect on the Higgs potential
- Observables

EW Baryogenesis

EW Baryogenesis

- Baryon asymmetry from first order EW phase transition



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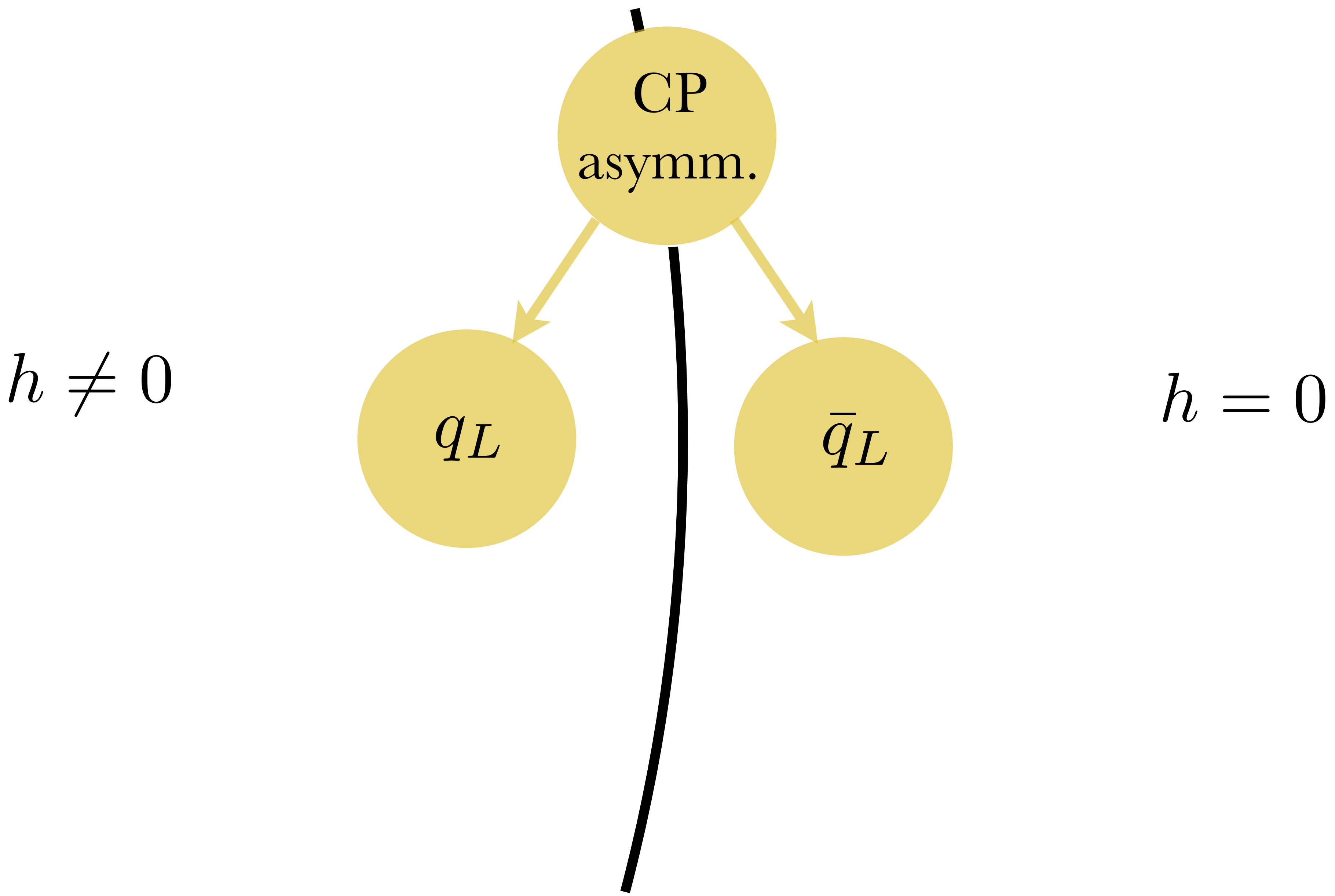

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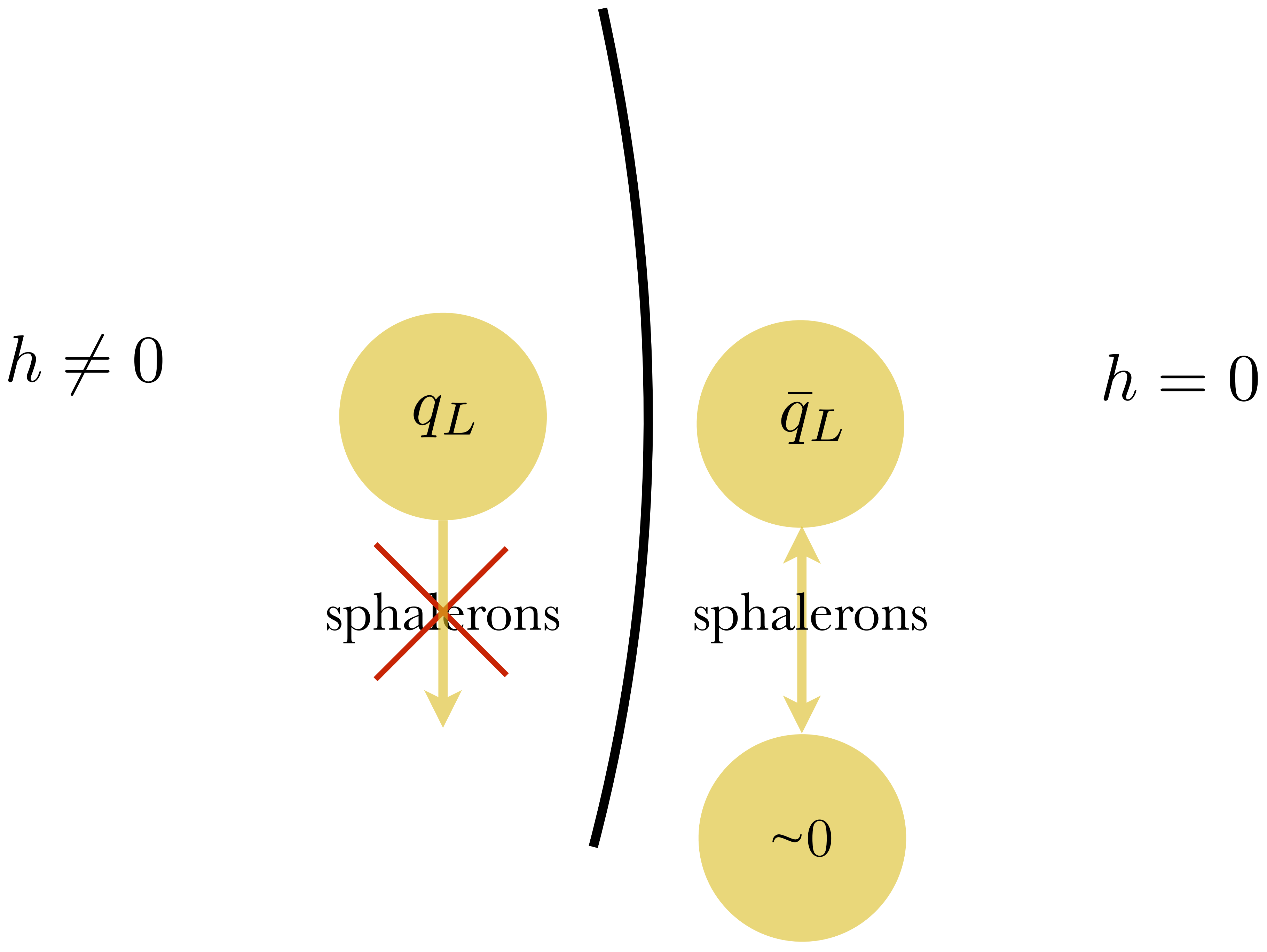

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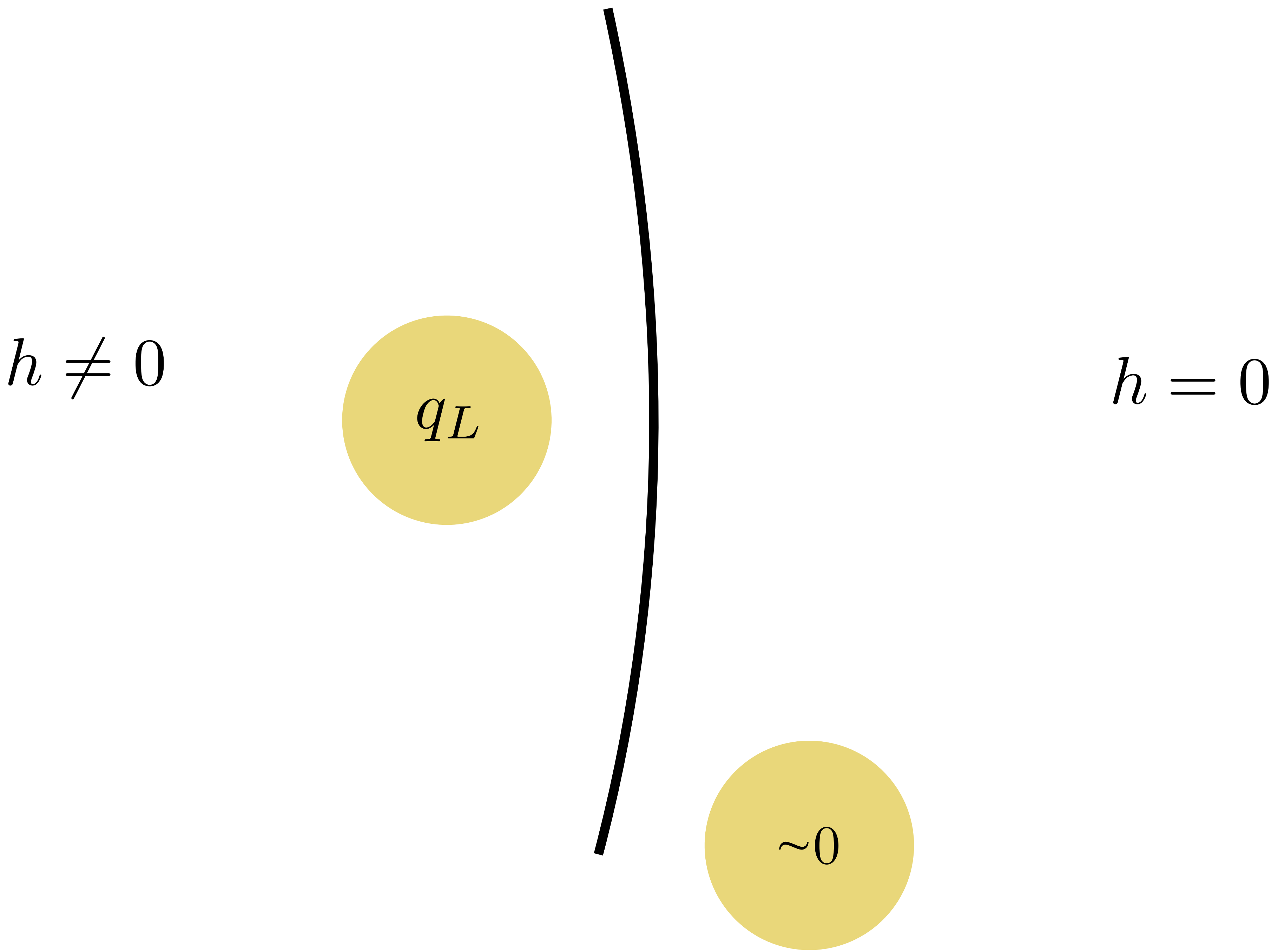

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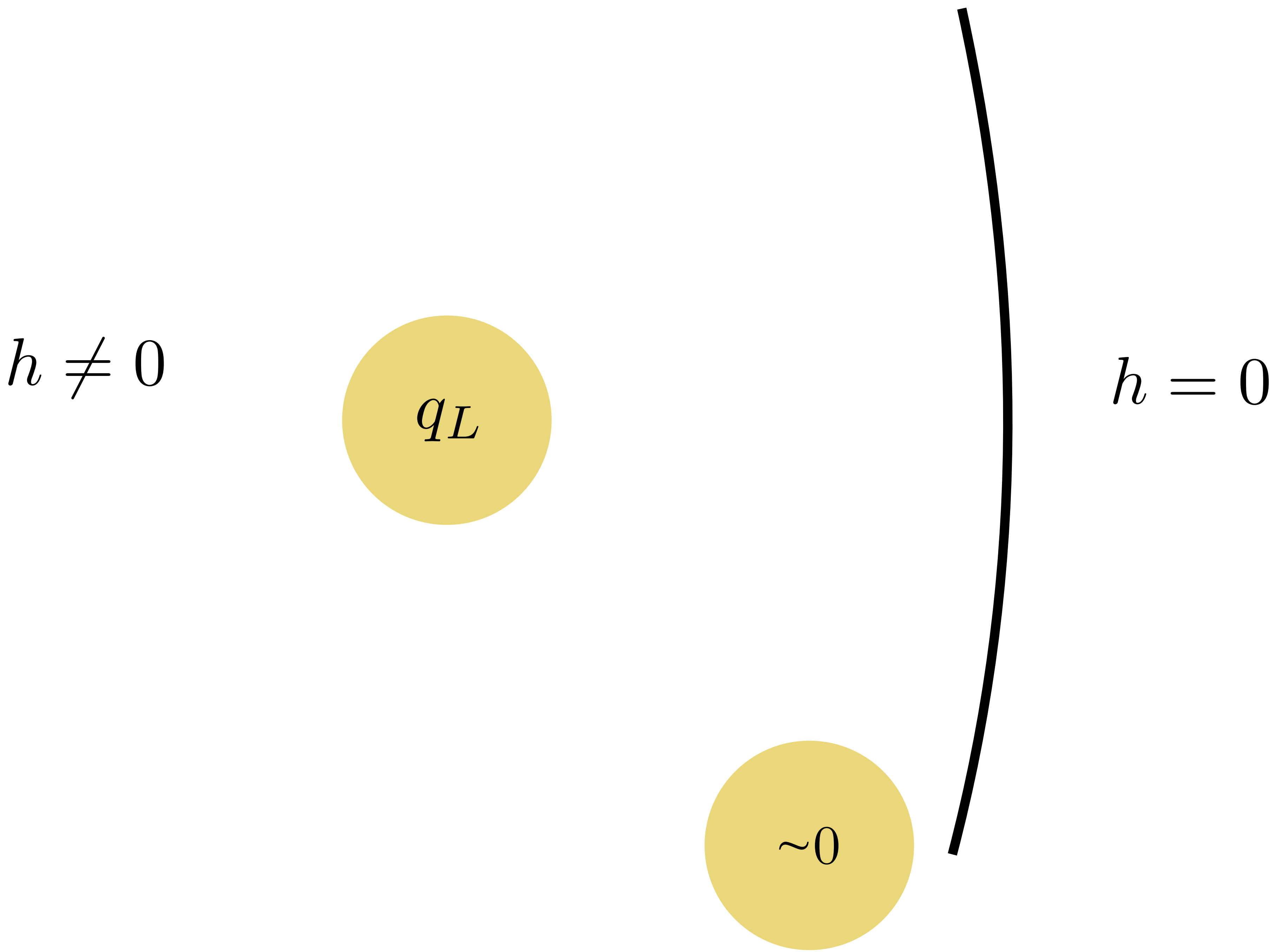

EW Baryogenesis

- Baryon asymmetry from first order EW phase transition

- Main requirements:

  - Source of CP violation
  - EWPT is strongly first order: $h/T > 1$

  $\Big\}$ not fulfilled in SM

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  } not fulfilled in SM

- Natural to consider TeV extensions of the SM which are also motivated by the EW hierarchy problem

Composite Higgs

(bottom-up*) Definition

* we identify the minimal number of necessary ingredients of the low-energy description, leaving aside possible UV completions

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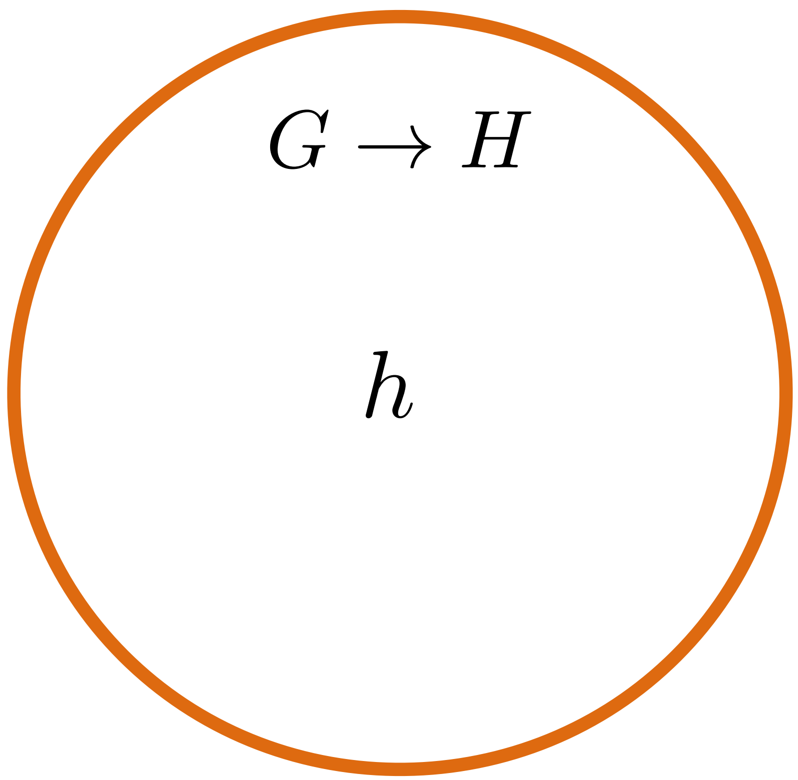

- new EW-breaking sector confines at a scale ~f
- G/H gives $\geq$ 4 NGBs

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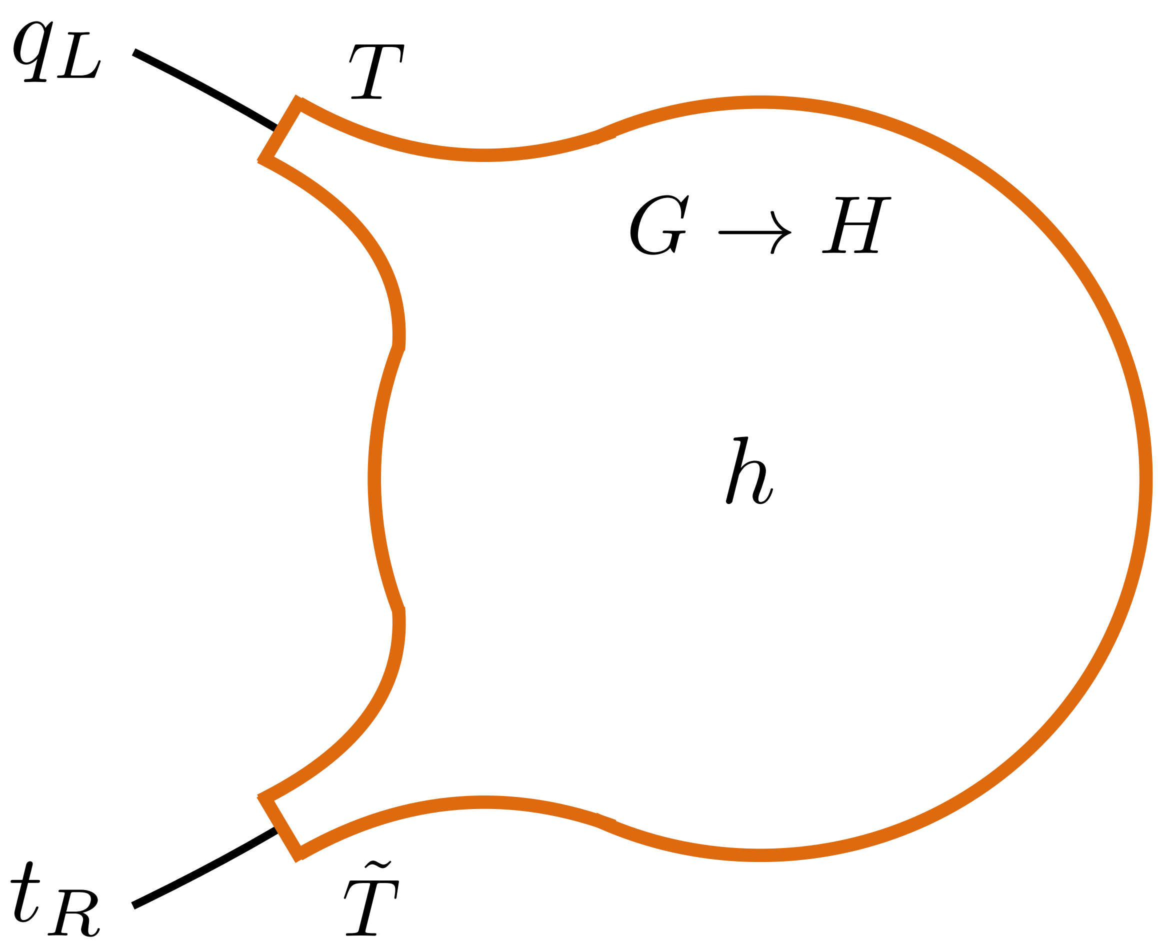

- new EW-breaking sector confines at a scale ~f
- G/H gives ≥ 4 NGBs
- elementary (~SM) fermions couple linearly (mix) to vector-like partners

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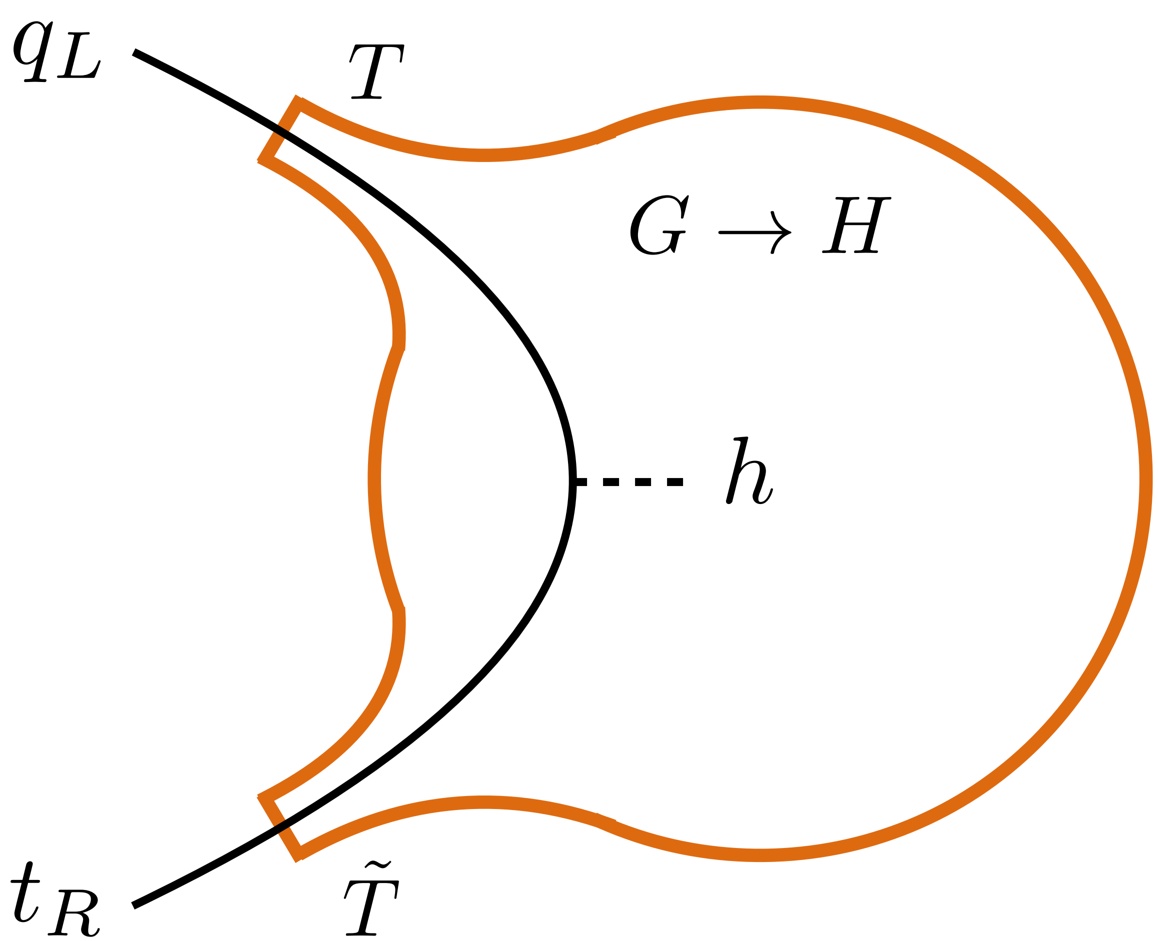

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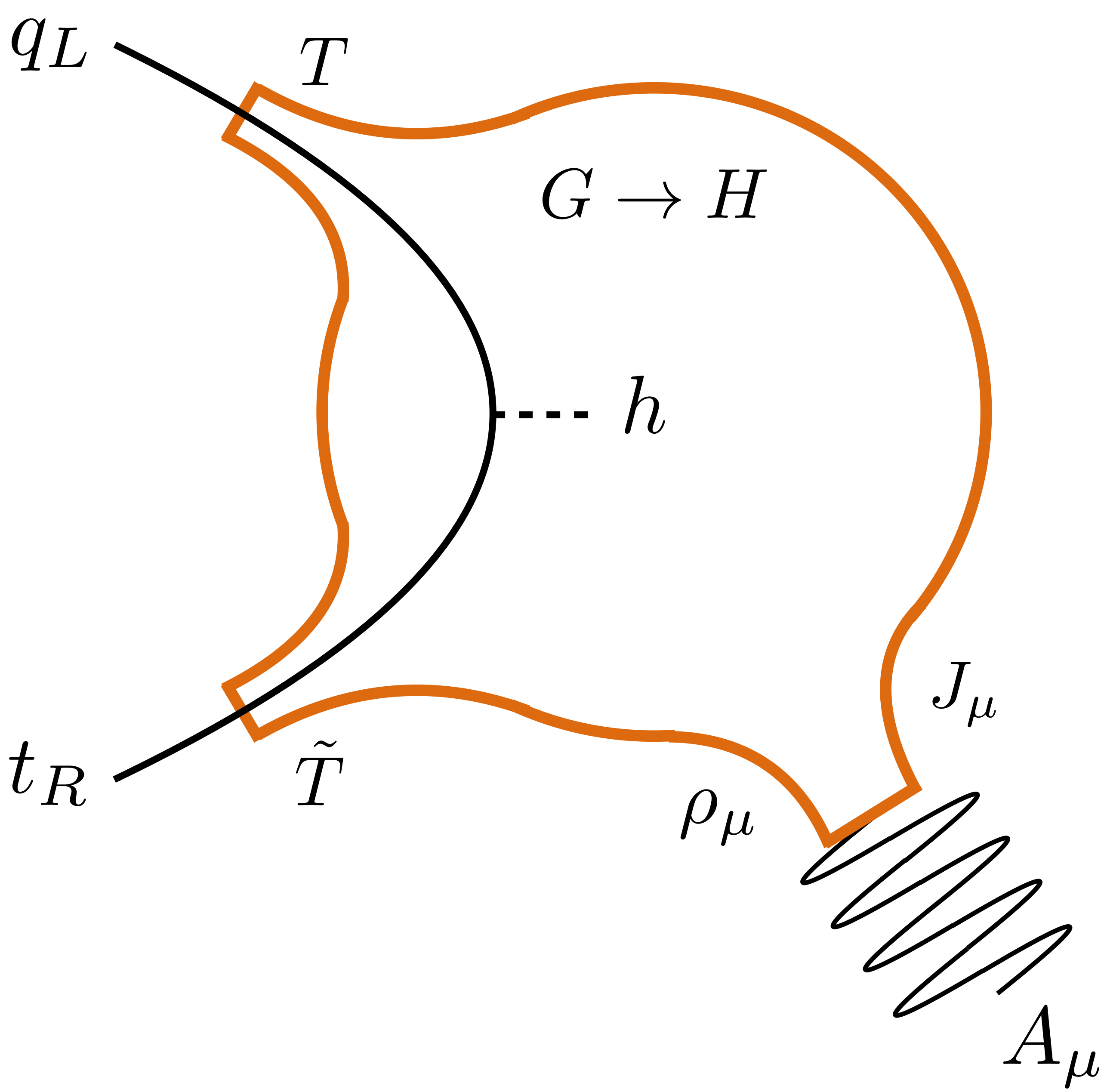

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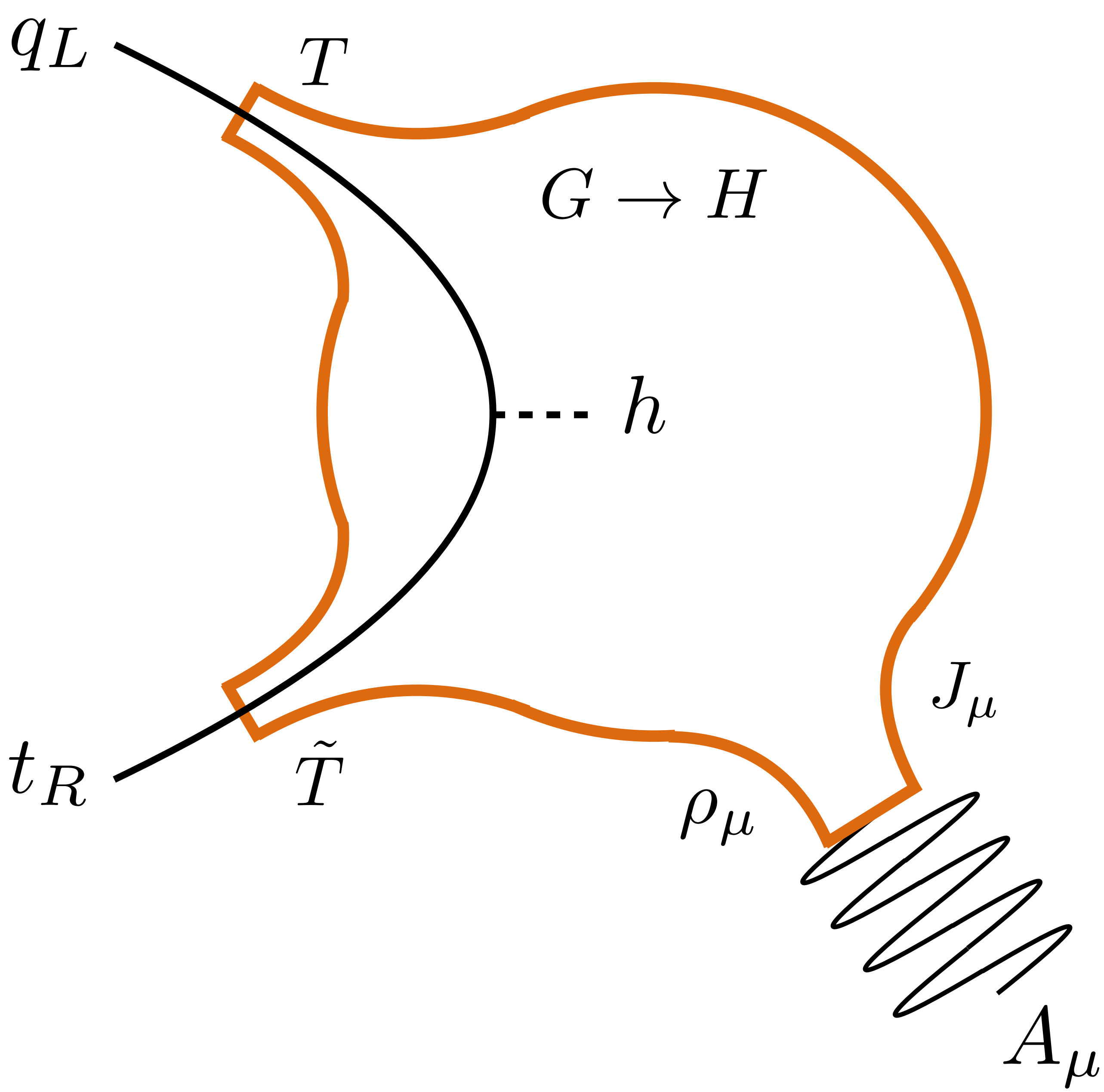

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- elementary - composite couplings break G

EW phase transition in CH

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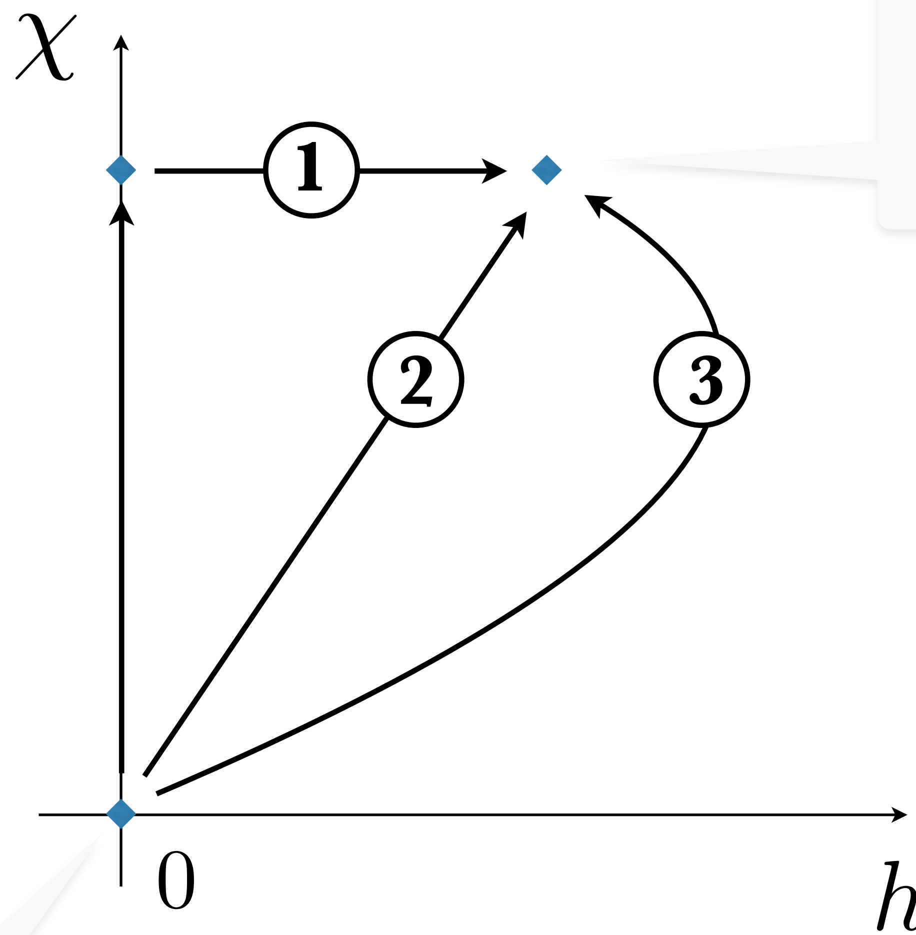


global minimum at
$T \ll f$

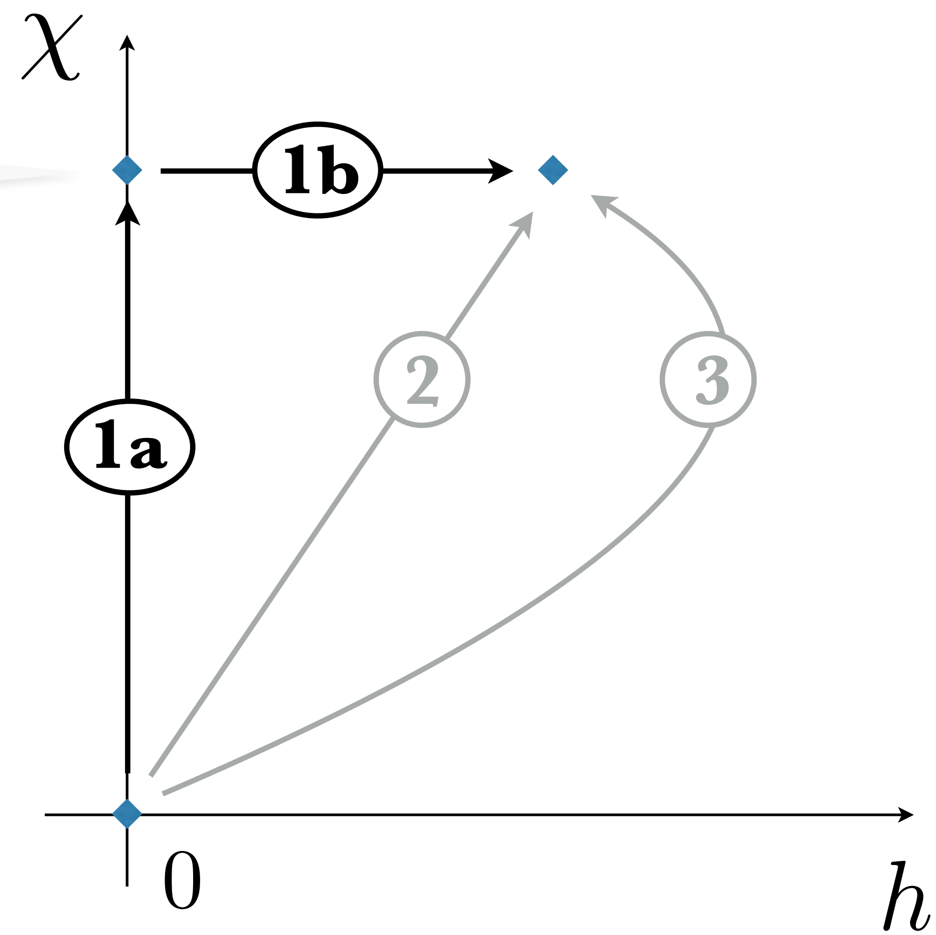
confinement and EWSB

global minimum at
$T \gg f$

deconfined strong sector
unbroken EW symmetry

EW phase transition in CH

- two-step transition (unless $T_R \lesssim f$)
- extra ingredients to make (1b) strong

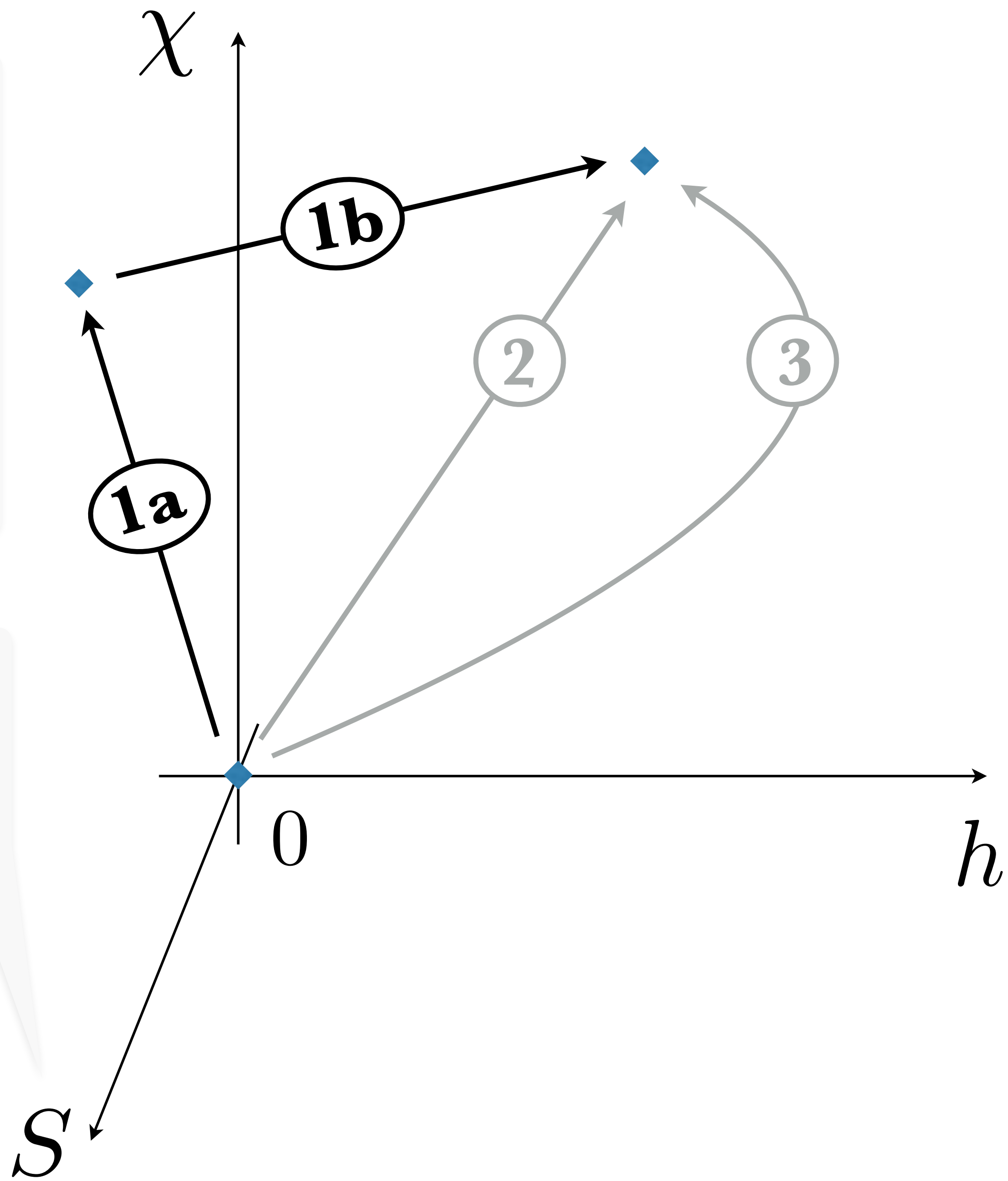


EW phase transition in CH

- two-step transition (unless $T_R \lesssim f$)
- extra ingredients to make (1b) strong

- e.g. extra pNGB S

Espinosa et al[1110.2876]



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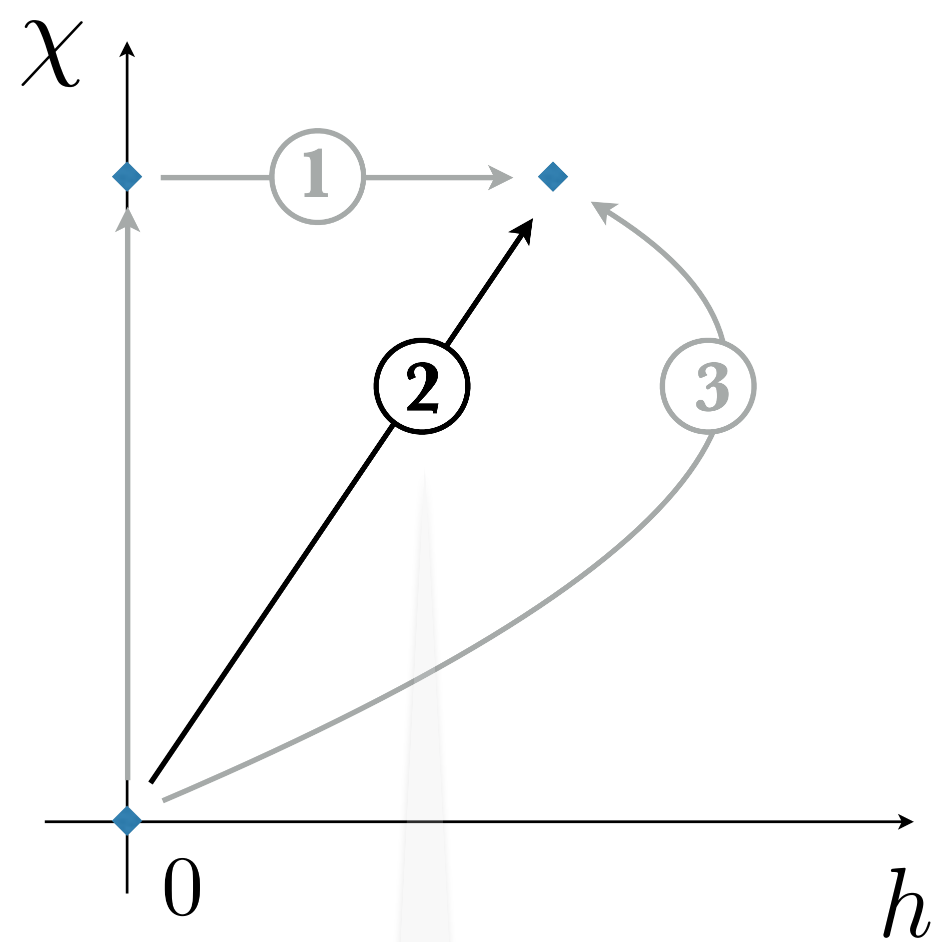
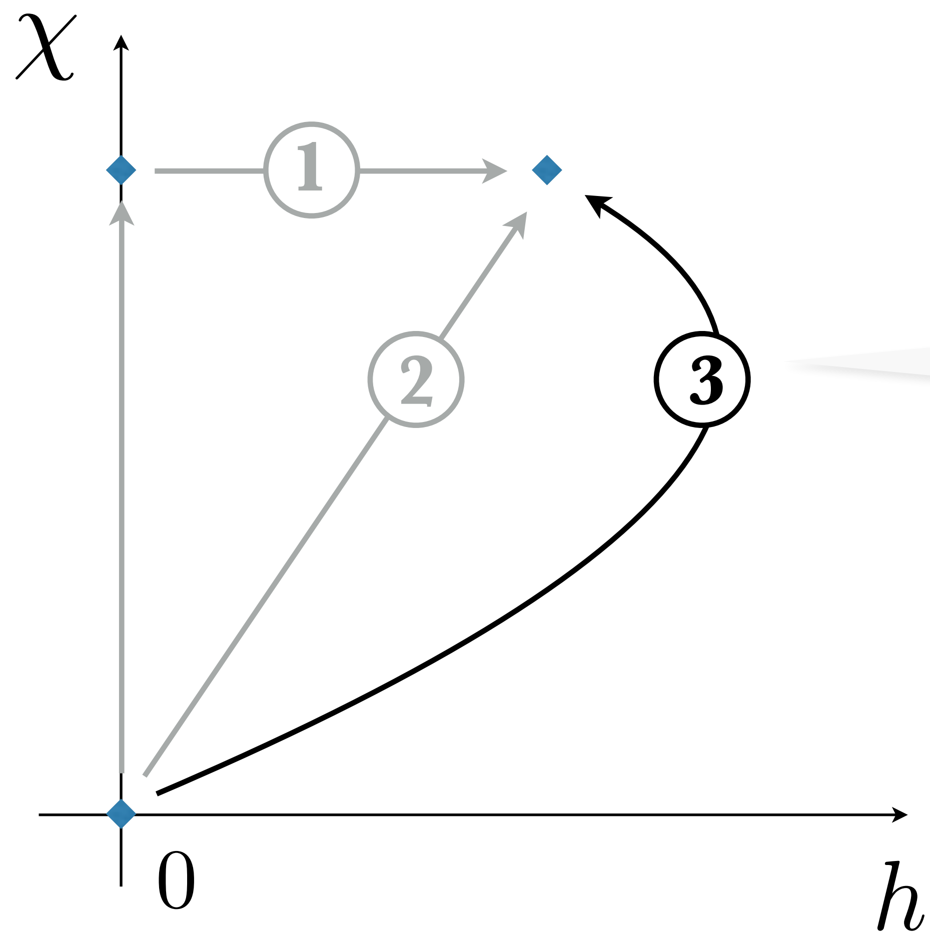


- EWPT accompanied by confinement transition
  $\rightarrow$ potentially strong EWPT
- trivial scaling of the Higgs vev
- was studied in RS set-up, e.g. Nardini et al[0706.3388]

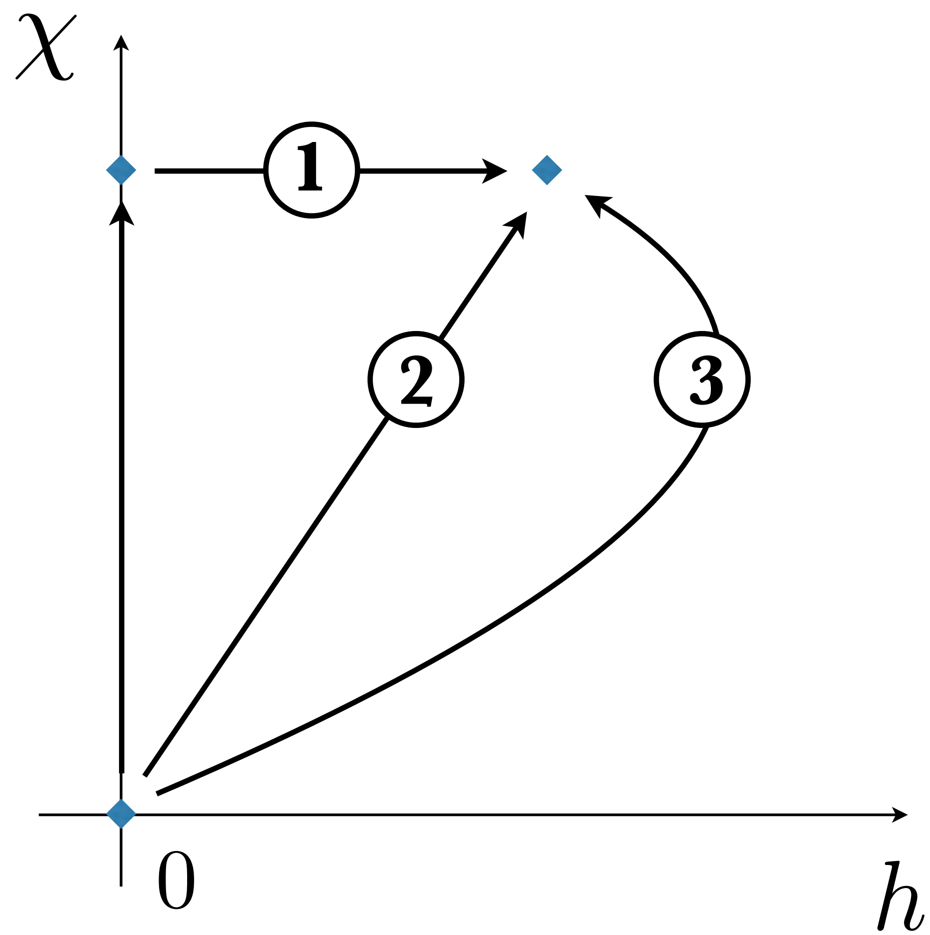
EW phase transition in CH



- EWPT + confinement
  $\rightarrow$ strong EWPT

- non-trivial $h(\chi)$
  important for baryon asymmetry

EW phase transition in CH



We will:

- find what is needed for (1), (2) or (3) to happen
- identify a viable CP violating source active during combined transition
- show that the CPV source can lead to (3) rather than (2)

Dilaton potential

Dilaton potential

- In general difficult to analyse phase transitions of strongly interacting theories

- Top mass, FCNC, UV/IR separation suggest that the strong sector is nearly conformal (~invariant and strongly coupled over a wide range of energies).

- One can expect a light dilaton χ to appear in the composite states spectrum

$$m_\chi < m_*$$

- Dilaton vev is related to the confinement scale

- One can hope to faithfully describe the strong sector phase transition in terms of SM + a single light degree of freedom

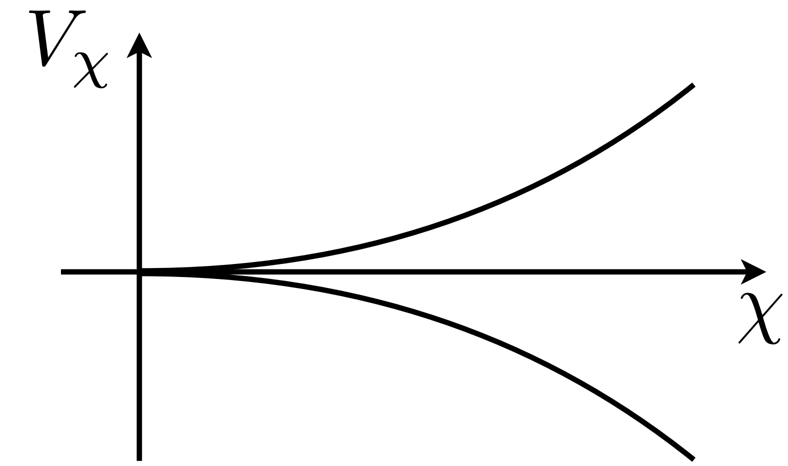
Dilaton potential

- Scale-invariant part

$$V_\chi = c_\chi g_\chi^2 \chi^4$$

g_χ - some typical coupling

c_χ - order-one number



- Insufficient to get a finite $\chi \neq 0$ unless $c_\chi = 0$

χ

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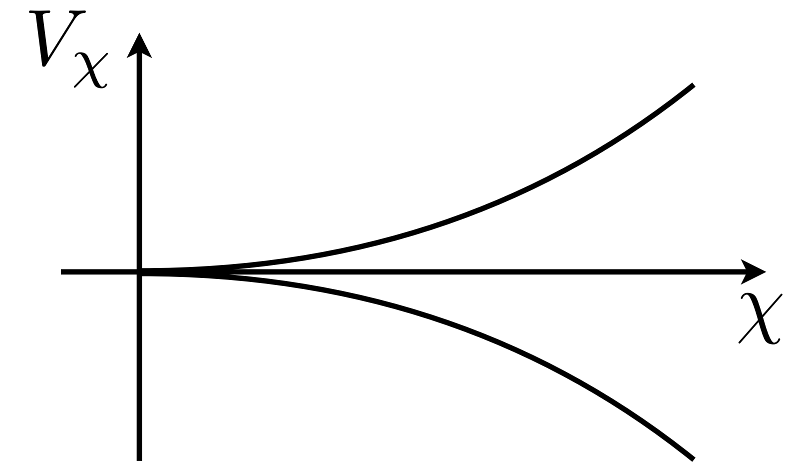

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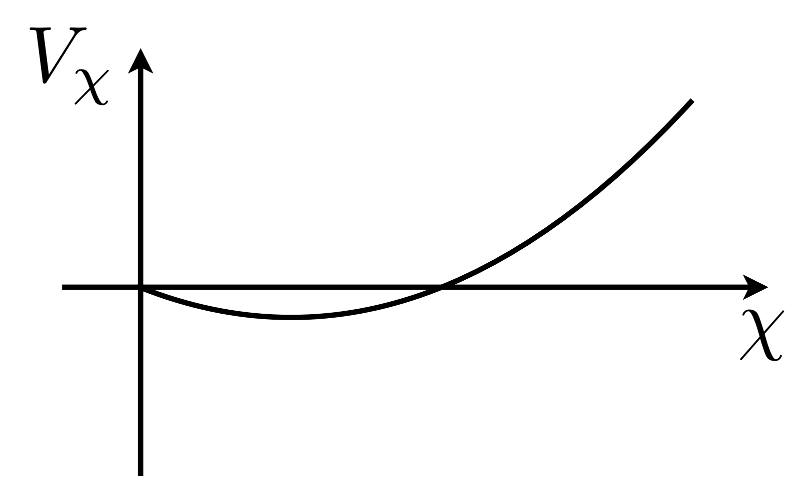
- CPR: source of explicit breaking $\epsilon \mathcal{O}_\epsilon$

$$\frac{\partial \epsilon}{\partial \log \mu} \simeq \gamma_\epsilon \epsilon + c_\epsilon \frac{\epsilon^2}{g_\chi^2}$$

- dilaton sets renormalization scale of epsilon

- Resulting potential admits a non-trivial minimum

$$V_\chi = c_\chi g_\chi^2 \chi^4 - \epsilon[\chi] \chi^4 + \ldots$$



Dilaton potential

- We trade epsilon and epsilon' for the dilaton mass and vev

$$V'_\chi[\chi_0] = 0 \quad \Rightarrow \quad \epsilon[\chi_0] = c_\chi \frac{g_\chi^2}{1+\gamma_\epsilon/4}\,,$$

$$V''_\chi[\chi_0] = m_\chi^2 \quad \Rightarrow \quad \gamma_\epsilon = -\frac{1}{4c_\chi}\frac{m_\chi^2}{g_\chi^2\chi_0^2}\,.$$

Dilaton potential

- What is g_χ?
- Assumption: underlying CFT is a large-N SU(N) confining theory
- For a glueball-like dilaton one expects

$$g_\chi \sim \frac{4\pi}{N}$$

$\rightarrow$ dual to the radion of previously studied 5D models

- 4D lattice simulations of confining nearly conformal Nc=3 theories suggest a light meson-like state, possibly a dilaton

$$g_\chi \sim \frac{4\pi}{\sqrt{N}}$$

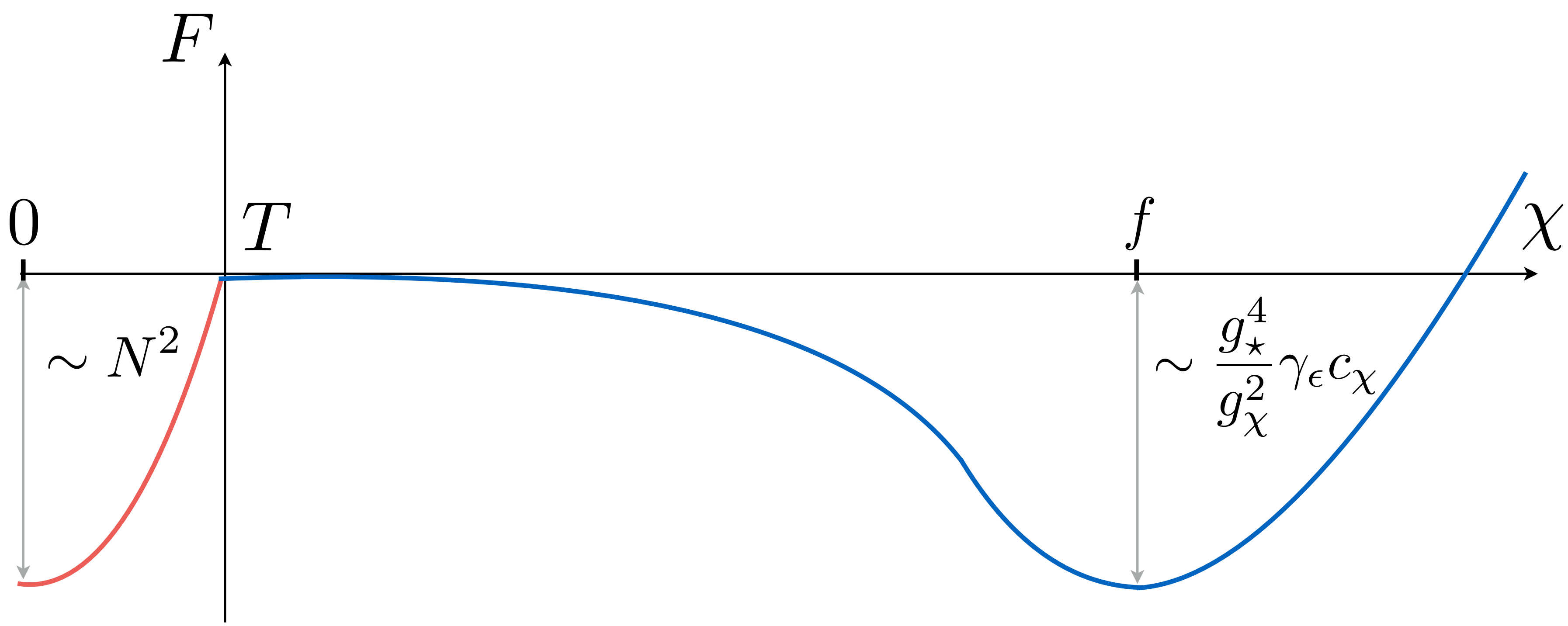
$\rightarrow$ different dynamics from the RS studies

Dilaton potential

- adding thermal potential

$$V_T(\chi = 0) \sim -N^2 T^4$$

- overall shape



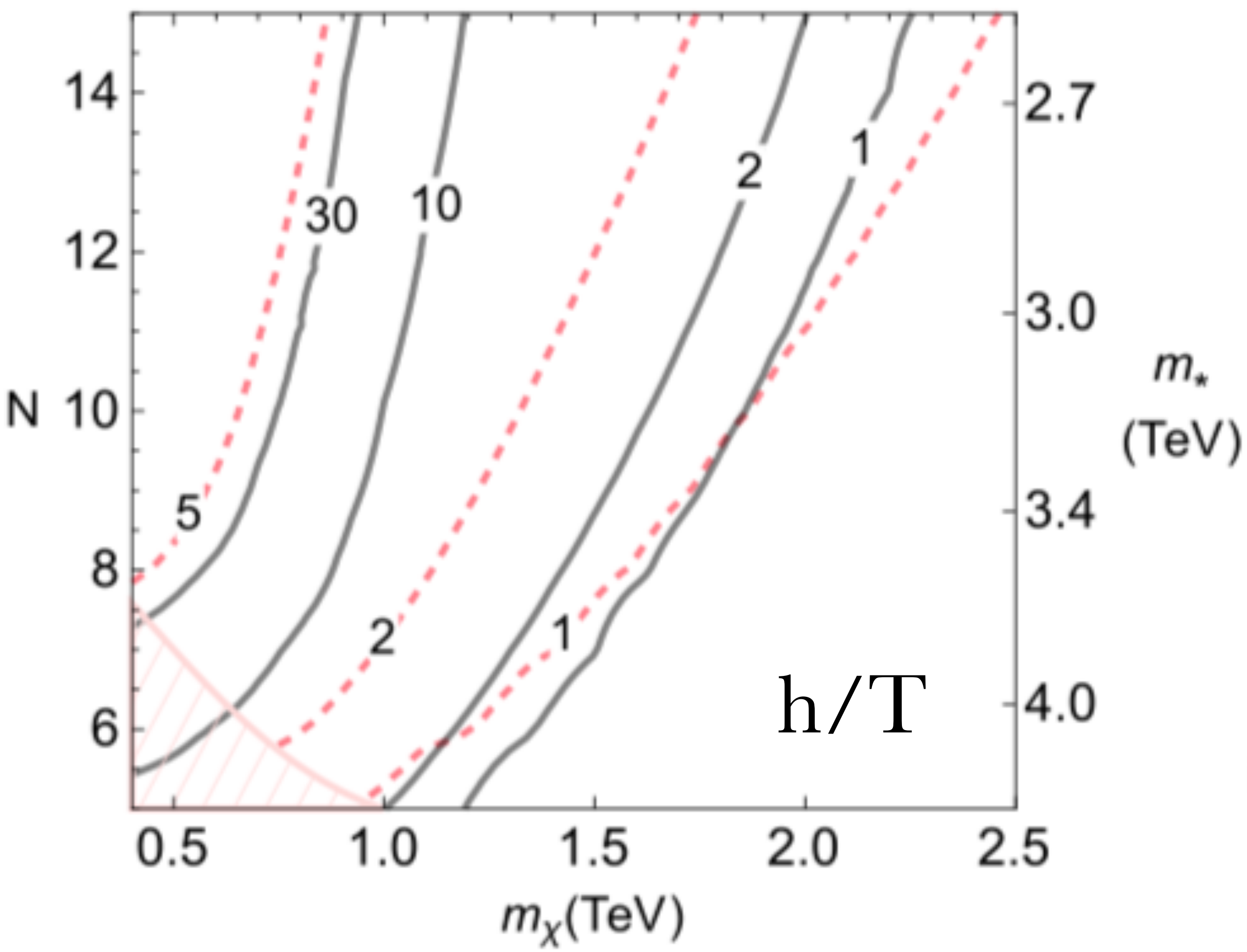
- critical temperature

$$T_c \propto \begin{cases} N^{-3/4}\,, & \text{for } g_\chi = 4\pi/\sqrt{N} \\ N^{-1/2}\,, & \text{for } g_\chi = 4\pi/N\,. \end{cases}$$

EWPT Strength

- we neglect the Higgs potential for the moment, assuming a tunelling independent on it (PNGB Higgs has a naturally suppressed potential)

EWPT Strength



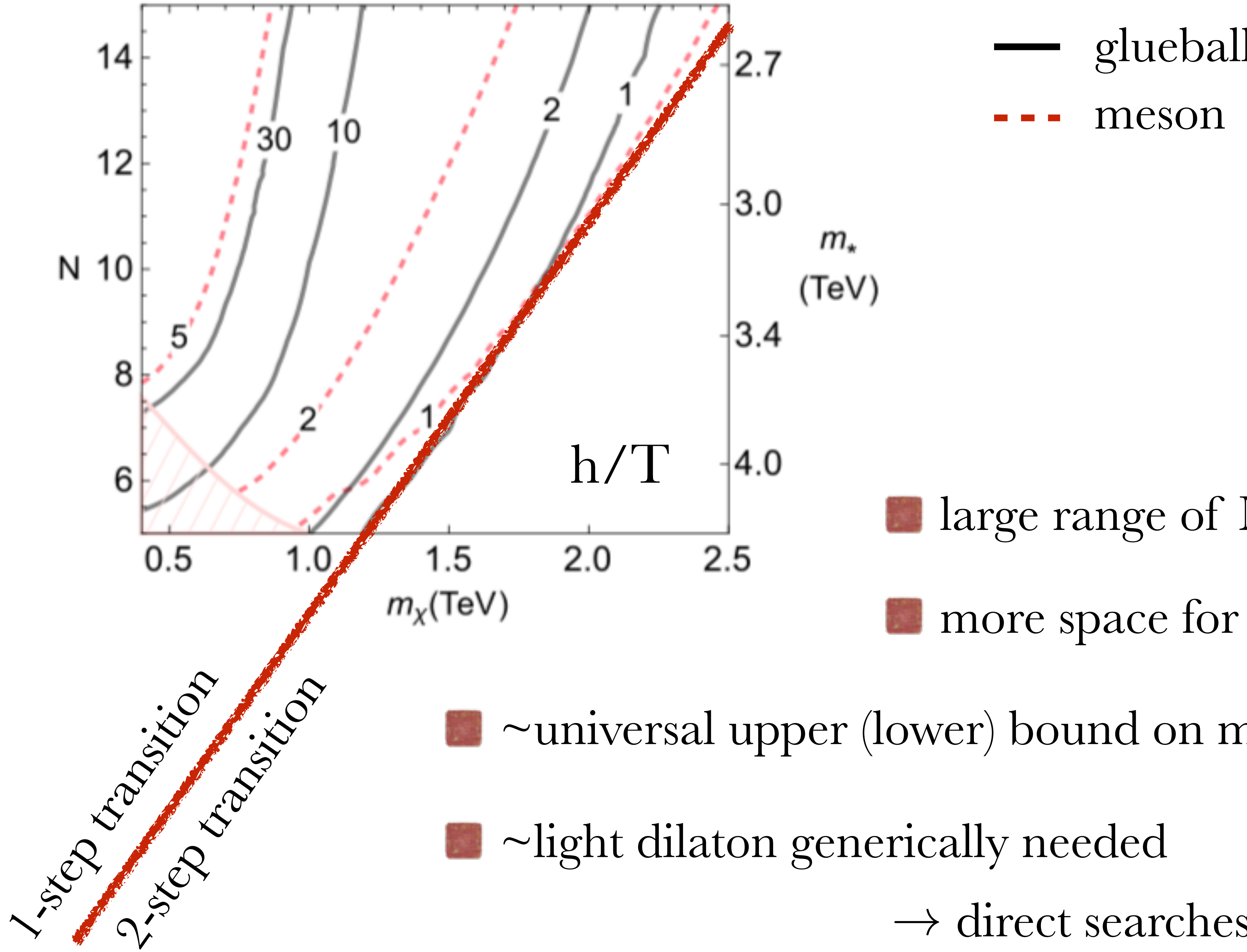
— glueball

- - - meson

- large range of N with h/T~1
- more space for the meson case
- ~universal upper (lower) bound on mchi (N)
- ~light dilaton generically needed

→ direct searches+Higgs physics

EWPT Strength



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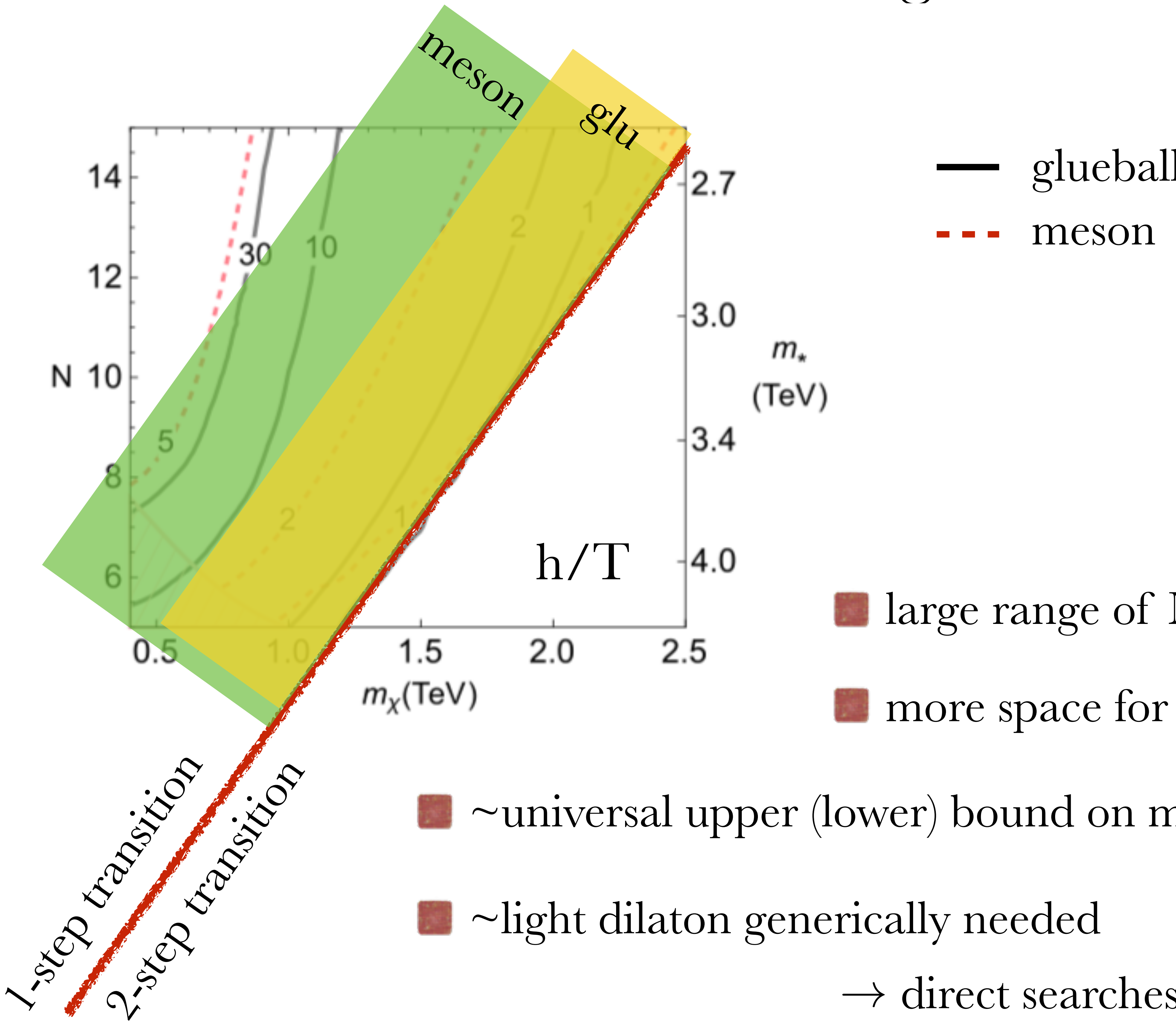

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→ direct searches+Higgs physics

CP violation from varying Yukawas
and
Higgs mass detuning

CP violation from varying Yukawas

- coordinate-dependent SM fermion mass can induce a net CP asymmetry in the plasma

$$S_{CPV} \sim \mathrm{Im}[V^\dagger m^{\dagger\prime\prime} m V]_{ii}$$

Bruggisser et al[1706.08534]

m - coordinate-dependent mass matrix

$$V^\dagger m^\dagger m V = m^2_{\rm diag}$$

derivative is taken wrt direction perpendicular to bubble wall

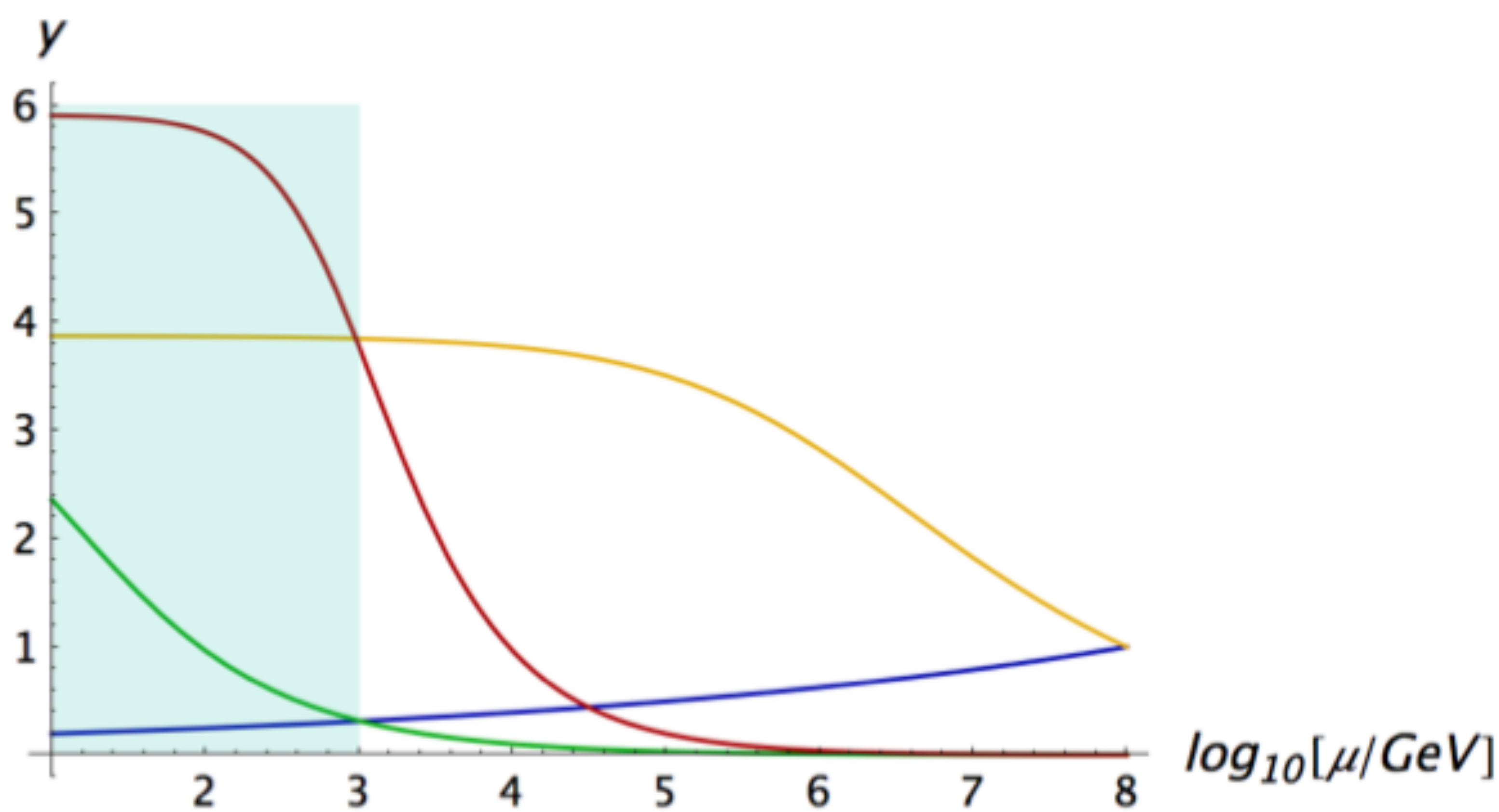
- dependence on h factors out, Scpv vanishes unless Yukawas vary between unbroken and broken phases

Varying Yukawas in CH

- SM masses come from partial compositeness

$$y_q \bar{q}\, Q + y_u \bar{u}\, U \quad \to \quad \lambda_q \sim y_q y_u$$

- mixings experience a sizeable scale dependence



- hence mixings depend on the dilaton value, which sets the renormalization scale

Varying Yukawas in CH

- what does $S_{CPV} \sim \mathrm{Im}[V^\dagger m^{\dagger\prime\prime} m V]_{ii}$ mean?
- two simple special cases to get CPV
  - single Yukawa with a varying phase

$$S_{\mathrm{CPV}} \sim \mathrm{Im}[m_t^{\dagger\prime\prime} m_t]$$

e.g. from $y_1 \bar{q}\, Q_1 + y_2 \bar{q}\, Q_2$

  - interplay of several quark mixings

$\rightarrow$ need for sizeable off-diagonal yukawas

$\rightarrow$ dependence on the flavour symmetries

Higgs potential detuning

- the Higgs potential is strongly affected by the mixings

  $$V_h = \alpha \sin^2 h/f + \beta \sin^4 h/f$$

  $\alpha \sim \beta \sim y^2$ - main source of shift sym breaking

  $f \sim \chi$ - condensate scale

- having $v \ll f$ requires to tune α and β

  $$\alpha = (v^2/f^2)\beta$$

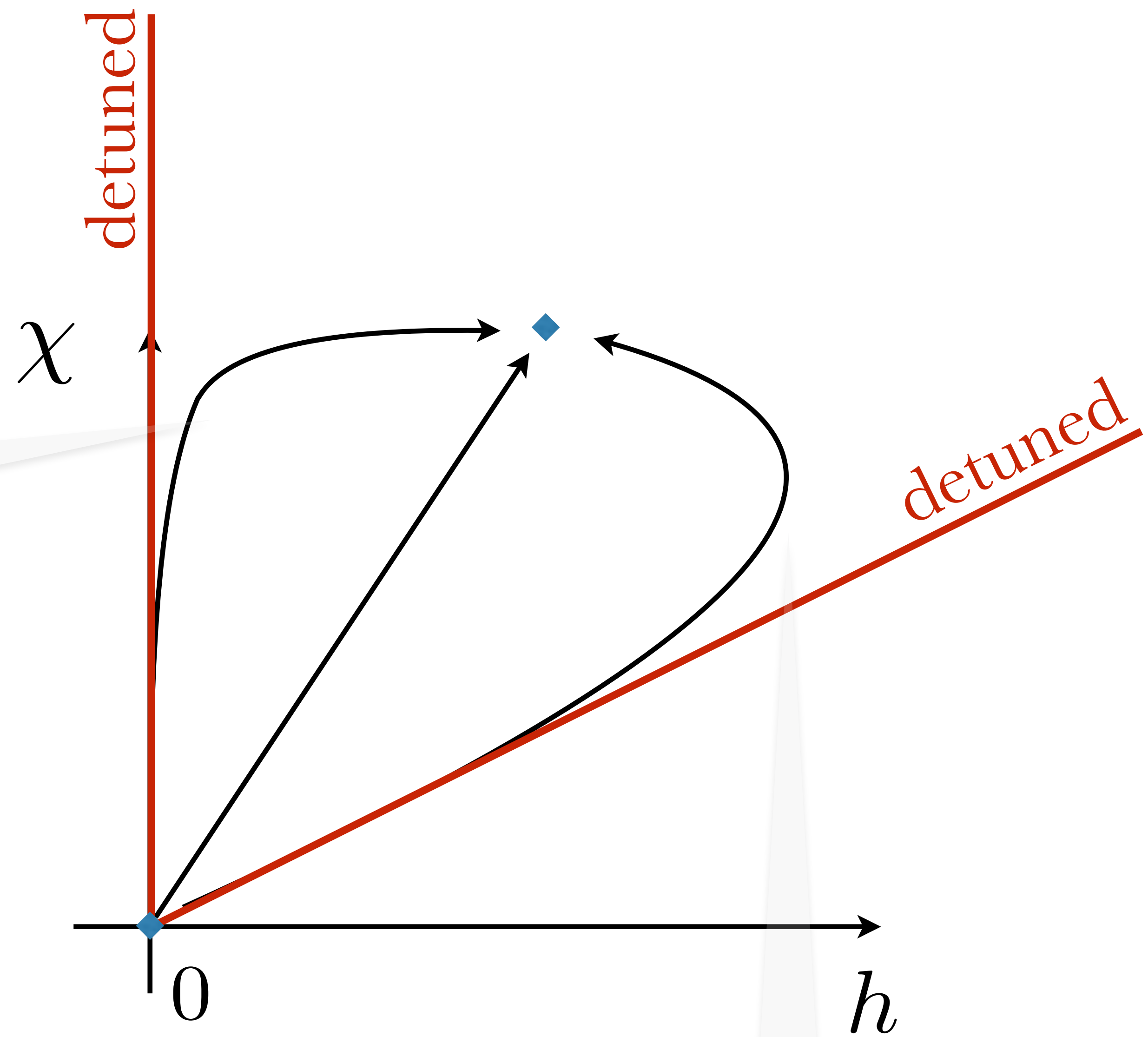
  from current exp data $v^2/f^2 \lesssim 0.1$

- mixing variation with χ generically make the potential detuned, so that

  $$h/\chi = \{0, \pi/2\}$$

Higgs potential detuning

- effect on the transition trajectory:



- no CPV

  $m_q = 0$

- in some cases also no CPV
- in others enhanced CPV

  $m_q \propto \sin^{1+m}(h/f) \cos^n(h/f)$

Summary of EWPT

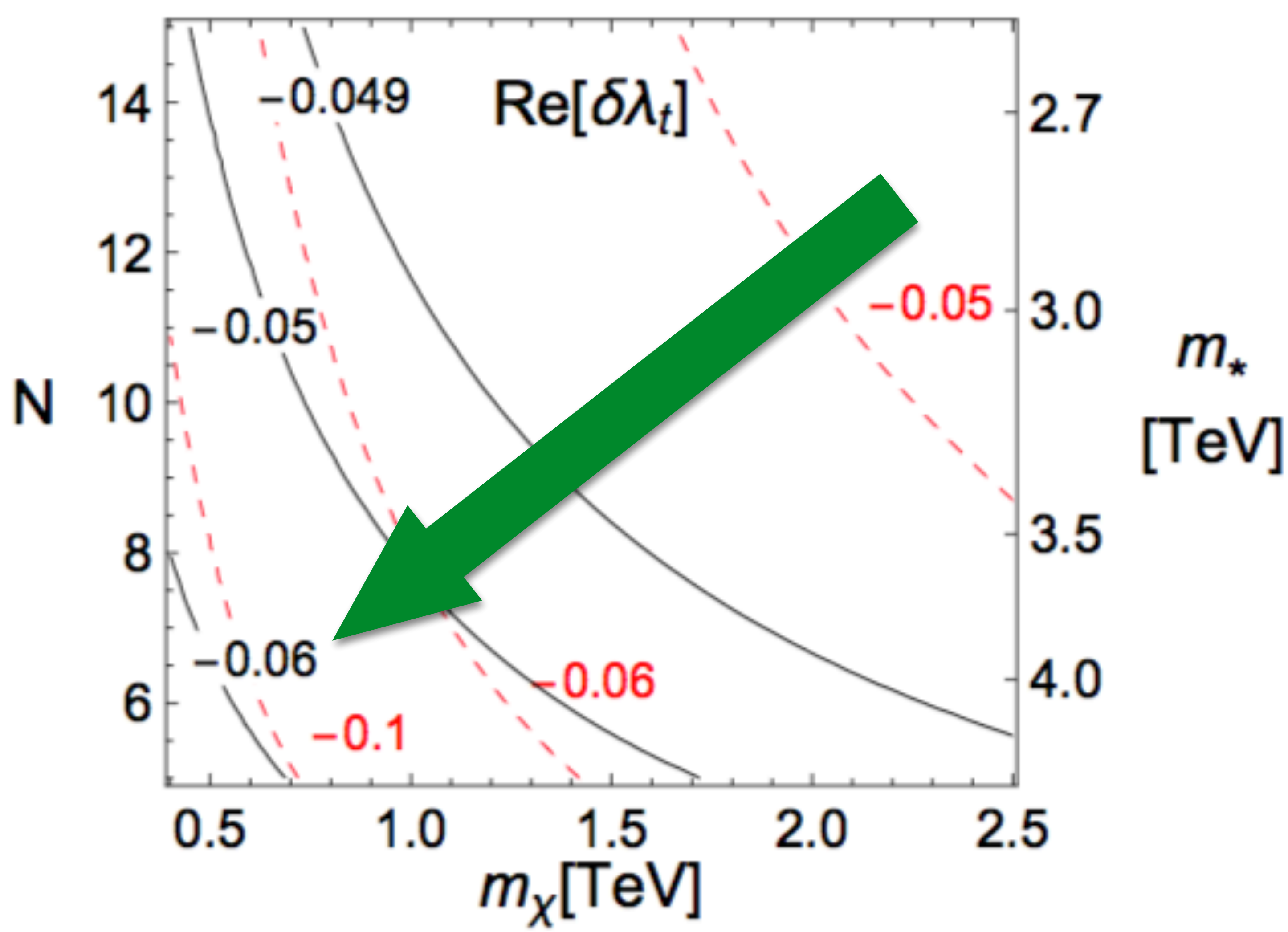
- one can obtain strong first-order EWPT
- CP asymmetry (and resulting baryon asymmetry) depends strongly on the symmetries of the model: flavour and global strong sector symmetry G.
- overall, the required baryon asymmetry can be obtained with little effort

Relevant observables

- direct searches for light dilaton

- Higgs physics: BSM effects comparable to generic CH contributions

$$[h - \chi \ \text{ mixing}] \sim \beta_y \sim S_{\text{CPV}}$$



$$v^2/f^2 = 0.1$$

Relevant observables

- EDM's
  - Higgs and dilaton couplings to SM fermions are complex

$$\lambda[\chi] q h t$$

$$\lambda_0 + \beta\, \chi/\chi_0$$

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complex

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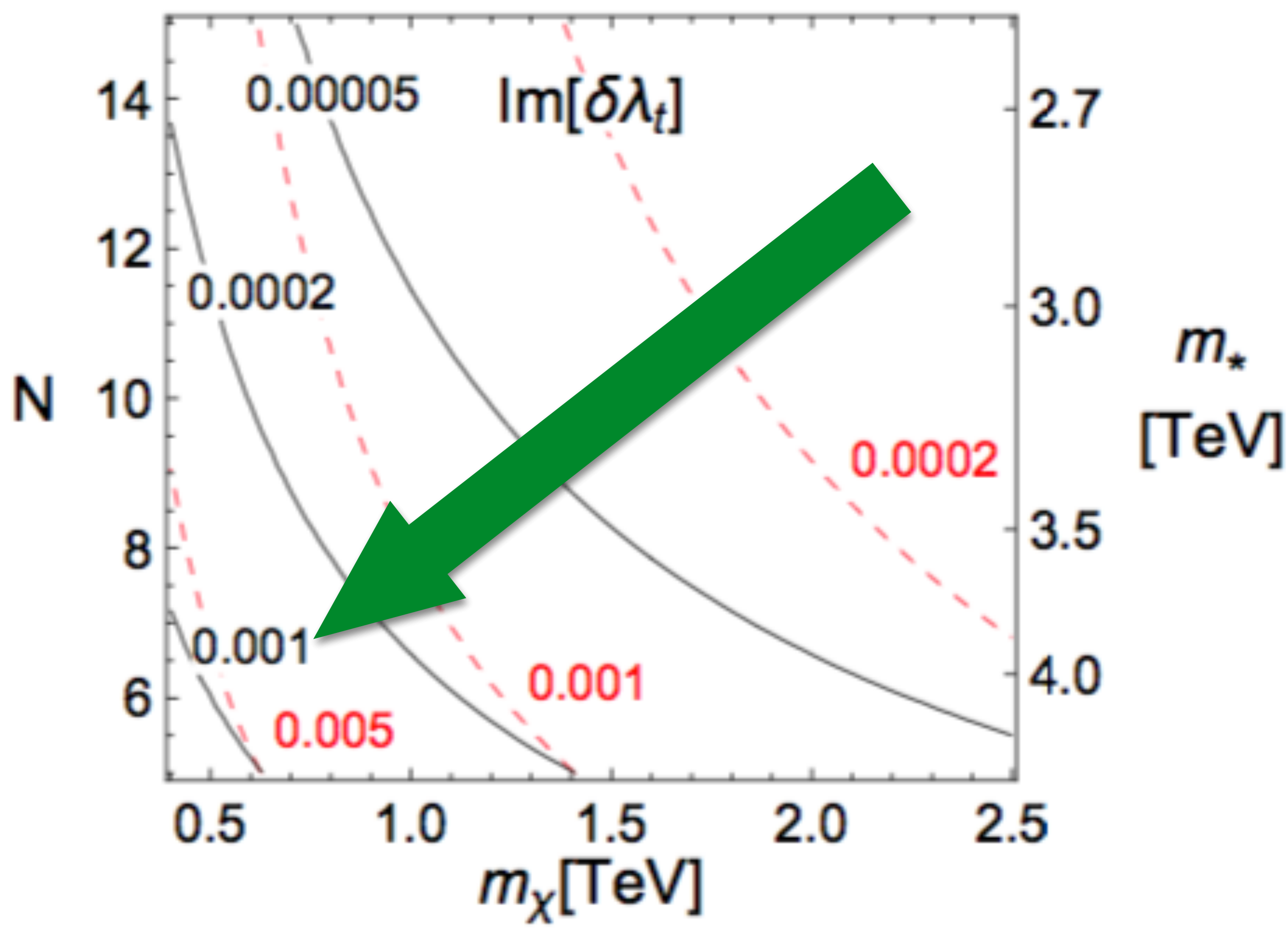
$$\lambda[\chi]qht$$

$$\lambda_0 + \beta\,\chi/\chi_0$$

$$s_\delta \hat{h} + c_\delta \hat{\chi}$$

complex

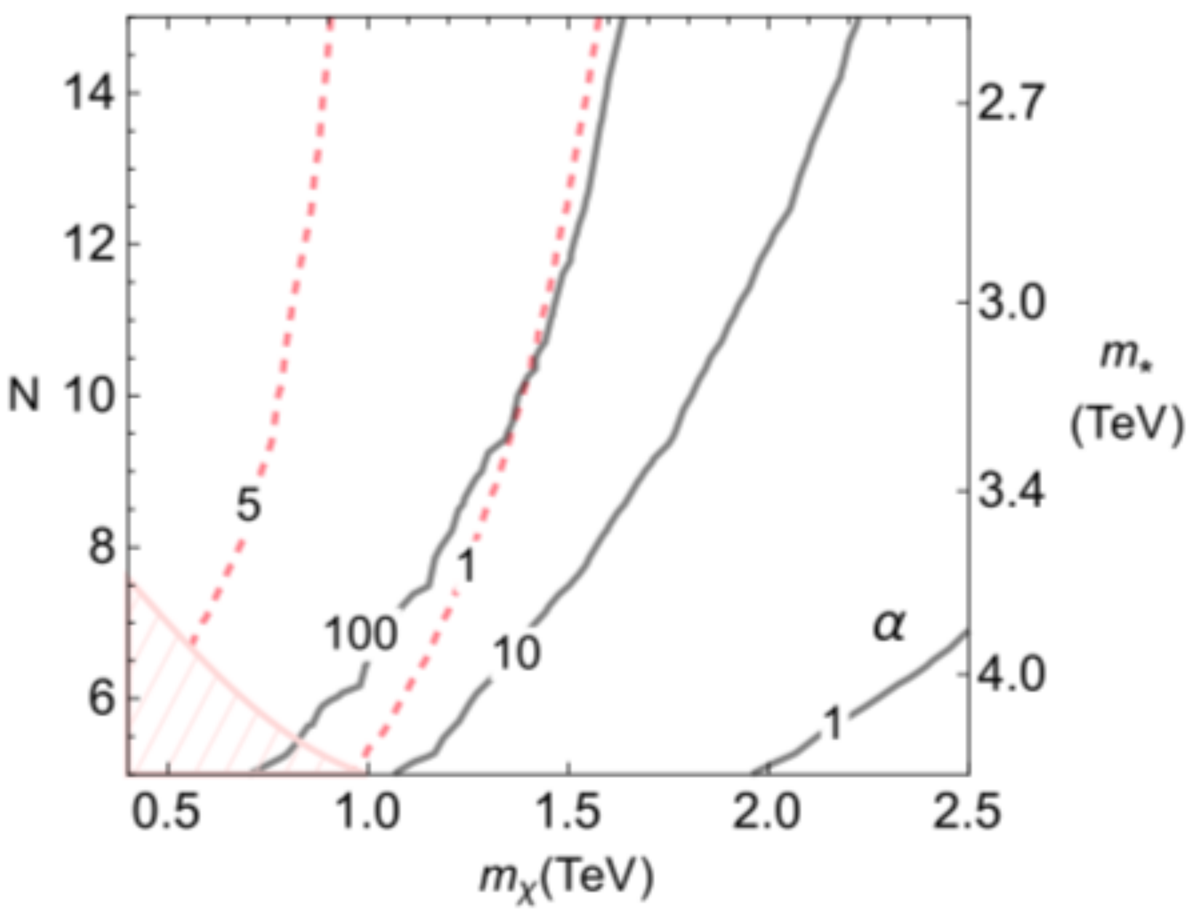
  - current bound $\mathrm{Im}[\delta\lambda_t] \lesssim 0.02$



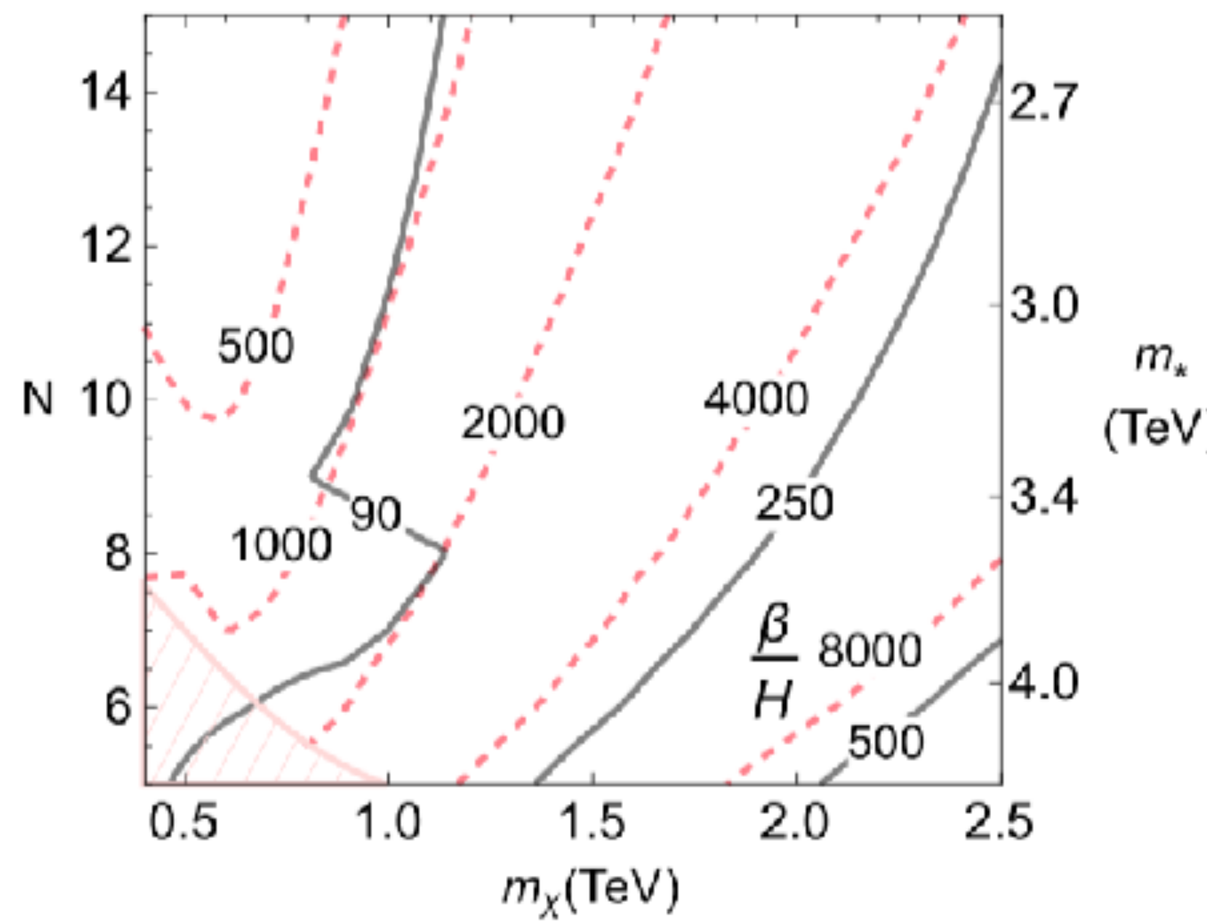
Relevant observables

- gravitational waves

$\alpha \sim$ latent heat



$\beta \sim$ transition rate

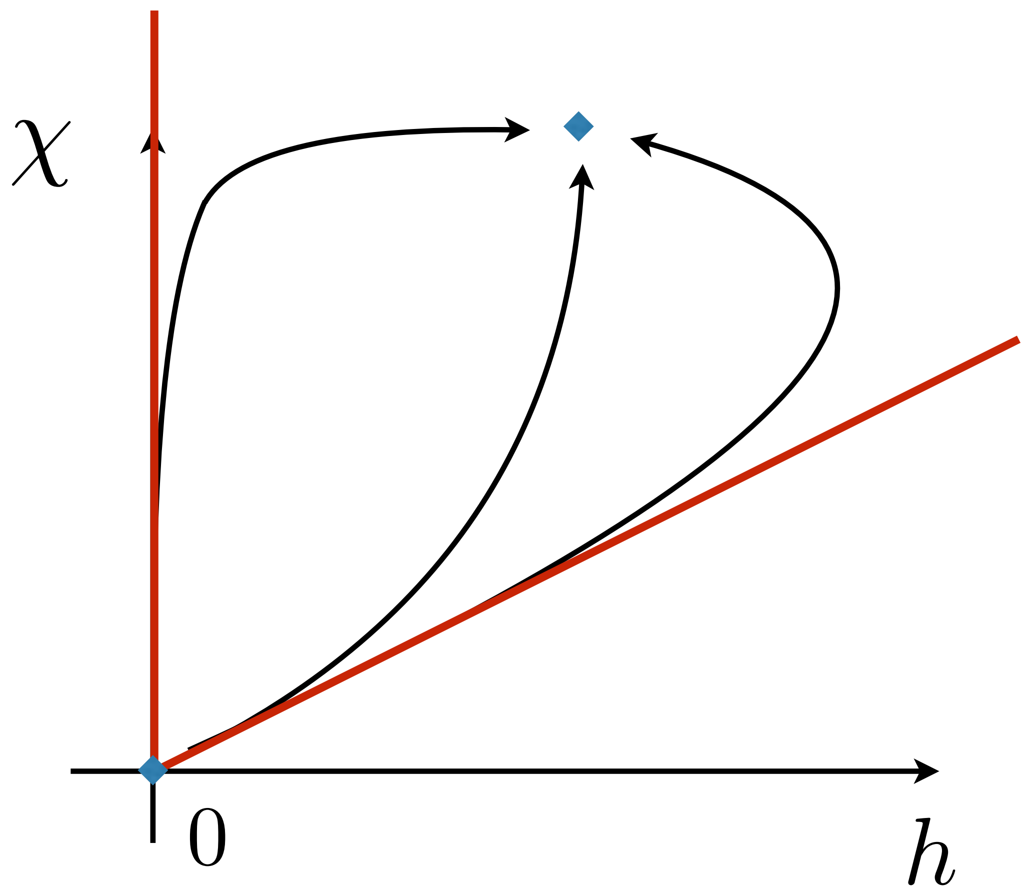


- LISA: $\alpha \gtrsim 0.1$ $\quad 1 \lesssim \beta/H \lesssim 10^4$

Cosmological imprint of fine tuning?

- Reece et al[1802.00444]: can EW fine tuning be tested from cosmology?

- phase transition trajectory depends on the tuning of the Higgs potential



$$(dh/d\chi) = (dh/dy)(dy/d\chi) \to \text{trajectory}$$

$$(dh/dy) \sim \text{tuning}$$

- tuning:

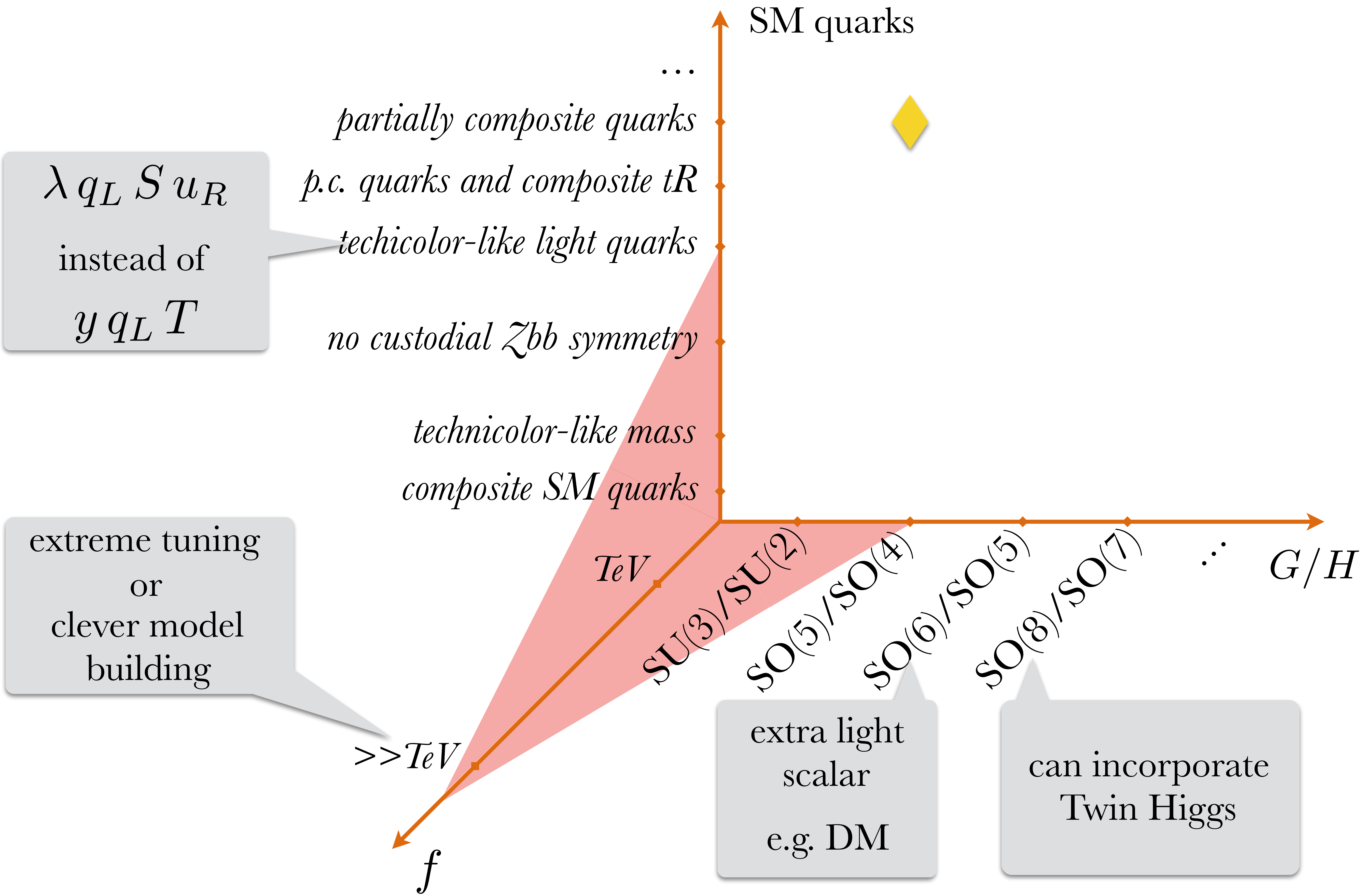
  $\to$ later displacement from the natural minimum

  $\to$ effect on baryon asymmetry

Conclusions

- It is natural to consider EWBG in CH context
- EWPT can be naturally strong
- There is a natural way to introduce a sufficiently large CPV
- With our CPV source (and more generally for the scale dependent Higgs potential) the coupled Higgs-dilaton evolution becomes non-trivial with important consequences for baryon asymmetry

CH Landscape



Phenomenology

- observed quarks are partially composite

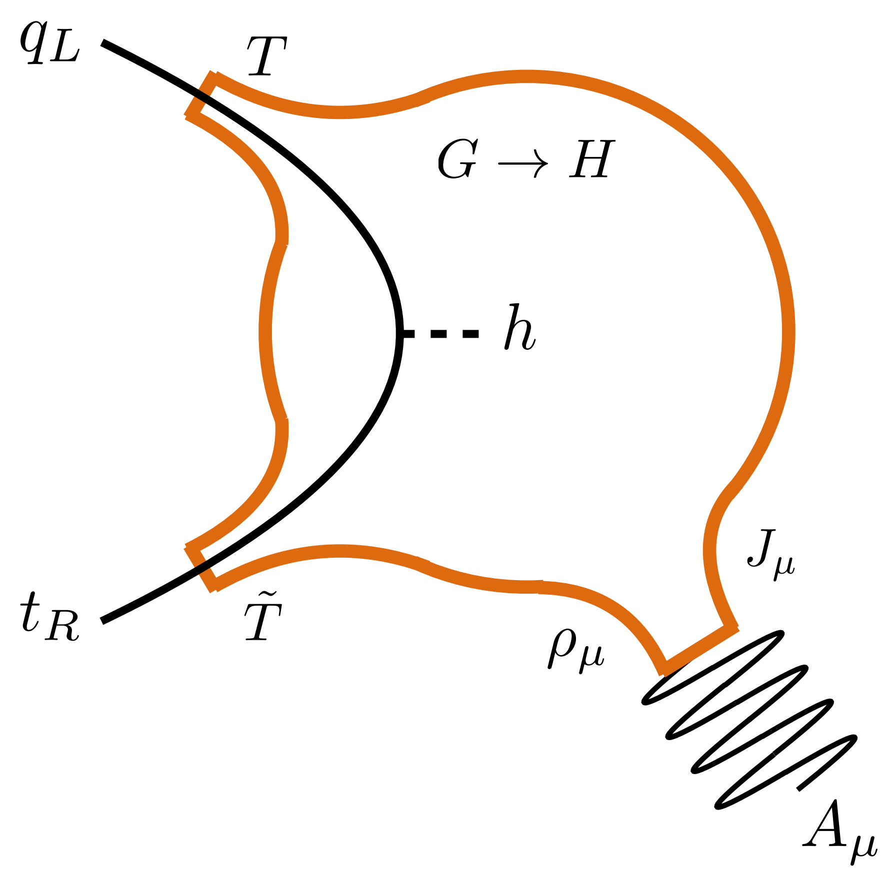
$$t_L = \cos\phi_L \, t_L + \sin\phi_L \, T_L$$

- *ffV couplings*
- *4f operators*
- *flavour physics*

- new resonances: fermions, vectors and scalars

$$\tilde{T} \quad T \quad \rho_\mu$$

- *collider searches for new states*
- *Dark Matter*
- *cosmological phase transitions*
- *S, T parameters*



- h is a pNGB

$$h \to f \sin\frac{h}{f} = h - \frac{h^3}{6f^2} + \ldots$$

- *hVV, hff*
- *h self-couplings*
- *S, T*

- EW couplings modifications

- *ffV couplings*
- *S, T*
- *TGCs*